

# MULTI-CRYSTALLINE SILICON HETEROJUNCTION SOLAR CELLS

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**ABSTRACT:** In this work we present the results we obtained by processing 1  $\Omega\cdot\text{cm}$  p-type alkaline textured multi-crystalline silicon wafers when a double hydrogenated amorphous/crystalline silicon heterojunction is applied to sandwich the substrate. At the sunward surface to form the emitter and at the rear side to act as back surface field. We investigate the efficiency limiting factors by evaluating the photogeneration mechanism and we address a way of improvement. Even if the obtained photovoltaic efficiency is not impressive (15%), it is worth to note that this result is one of the very few results obtained on hydrogenated amorphous/crystalline silicon heterostructure based on p-type textured multi-crystalline silicon wafer, and the best published up to now.

**Keywords:** Silicon, Heterojunction, a-Si.

## 1 INTRODUCTION

The hydrogenated amorphous/crystalline silicon (a-Si:H/c-Si) heterostructure have recently attracted new interest since have been deputed as one of the way to get close 25% of cell efficiency [1]. While very interesting results have been obtained on mono-crystalline silicon substrate, the silicon heterojunction (SHJ) based on multi-crystalline silicon (mc-Si) wafers still presents many aspects to be addressed and some questions still wait an answer [2-4].

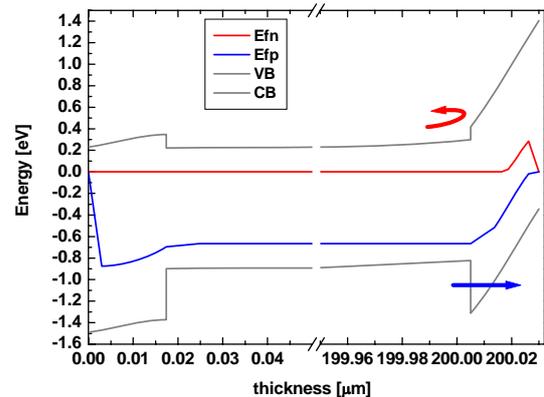
Efficiency and carrier transport properties of a-Si:H/c-Si heterojunction solar cells are significantly affected by the c-Si surface conditionings prior the plasma deposition process and, of course, by the amorphous silicon deposition conditions.

The hydrogen plasma treatment could result in a useful defect (like dislocations and grain boundaries) passivation for multi-crystalline silicon. Likewise, if for mono-crystalline the choice of silane as a precursor gas for the amorphous deposition could not be the best and tetrafluorosilane should be preferred, for multi-crystalline it seems the right choice, again thanks to the hydrogen defect passivation. Moreover surface treatments, prior the amorphous silicon deposition, able to reduce the surface roughness and the steps between individual grains, must be investigated in order to avoid micro-shunt that can affect the open circuit voltage of the photovoltaic device.

In this work we present the results we have obtained processing 1  $\Omega\cdot\text{cm}$  p-type alkaline textured multi-crystalline silicon wafers when a double a-Si:H/c-Si is applied to sandwich the substrate. At the sunward surface to form the emitter and at the rear side to act as back surface field (BSF). We have investigated on the efficiency limiting factors, and we have numerically modeled the solar cell internal quantum efficiency (IQE) to evaluate the photogeneration mechanism. By that we were able to estimate the thicknesses of the amorphous layers, the diffusion length of the minority carriers ( $L_n$ ) and the back surface recombination velocity ( $S_b$ ). We have also compared the performances of our heterostructure device to that of an industrial high efficiency solar cell, fabricated on sister substrate with a high temperature process, having a phosphorous diffused

emitter and an alloyed aluminum/silicon back surface field (P-diffused and Al-BSF).

## 2 TECHNOLOGICAL ISSUES



**Figure 1:** Simulation with DIFFIN of the ideal band bending and carrier concentration at the back side of our heterostructure solar cell in AM1.5G condition. The dark lines correspond to the conduction and valence band.

For n-type a-Si:H/p-type c-Si heterojunction surface passivation is still a challenge in order to obtain high open circuit voltage (>700 mV). Different approaches have been investigated to improve the interface with the c-Si substrate [5]. In addition, considering the p-type based HIT [3] cell, the band offset at the p-type c-Si/intrinsic a-Si:H/p-type a-Si:H interfaces, at the rear of the device, is influencing the photogenerated carriers collection from the back contact [6]. While the offset in the conduction band and the band bending can be useful as back surface barrier against electrons, the higher band offset in the valence band should behave as a barrier for the holes collection. A simulation of the back side behavior of the double SHJ solar cell based on p-type mc-Si wafer, by DIFFIN program, elsewhere presented [7], clearly describes this ideal situation, as reported in

Figure 1.

The key issue for the result of 17% efficiency on the heterostructure solar cell based on p-type monocrystalline silicon, presented by the authors in 2003, was the chromium silicide (CrSi) [8]. We found that the formation of a CrSi film occurs at room temperature at the interface between amorphous silicon and chromium, and can be obtained by vacuum evaporation of chromium followed by a wet metal etching, performed with a solution of 30 g ceric ammonium nitrate, 9 ml glacial acetic acid and 200 ml deionized water. This process does not remove the CrSi film, but it just etches the metal in excess. The extension of this high conductivity layer inside the n-type doped a-Si:H has been estimated to about 10 nm [9]. Further investigation reduced this depth to few nanometers. It is important to note that the CrSi formation is independent from the electronic properties of the n-doped a-Si:H. In particular, we have also observed the presence of CrSi on n-layers grown at room temperature. Moreover this layer does not introduce any further absorption to the n-type doped a-Si:H. After several tests on amorphous silicon films, we found that the CrSi is formed only on n-type amorphous film, while its formation unluckily was inhibited on p-type or intrinsic material. Therefore we have adopted a different approach by adding a ultra thin n-doped amorphous silicon film ( $\delta n$ ) deposited on the top p-type a-Si:H layer. This technological step has allowed us to form the CrSi film on the p-type a-Si:H-layer [10]. Very similar effect also happens on a p-type doped a-SiC:H. It is worth pointing out here that the p- $\delta n$  structure does not behave as a junction due to the tunneling current caused by the high defect density of the doped layers. Then, this new kind of layer can be adopted in the heterojunction solar cell process technology in order to overcome the problem of low doping value and high activation energy of the p-type a-Si:H or p-type a-SiC:H layers used as a window layer in the heterostructure devices based on n-type crystalline silicon, or as back contact and BSF formation in the heterostructure devices based on p-type crystalline silicon.

### 3 EXPERIMENTAL

To fabricate heterostructure solar cells we have used 106 cm<sup>2</sup>, 210  $\mu$ m thick, 1  $\Omega$ \*cm boron doped, multi-crystalline silicon as-cut wafer. A cross section of the solar cell is depicted in Figure 2.

This device presents a double heterojunction with silicon wafer: one at the front side, as Ag-grid/ITO/n-type a-Si:H/intrinsic a-Si:H; and the other at the back side, as intrinsic a-Si:H/p-type a-Si:H/ITO/Al. We have alkaline textured and industrially cleaned the wafer and then, after a 1% HF dip we have deposited the amorphous silicon layers in a three chambers 13.56 MHz RF PECVD reactor, using always the following conditions:

- 28 mW/cm<sup>2</sup> RF power density;
- 200 °C temperature;
- 300 mTorr pressure, and

adding the following gas mixtures:

- 1) 40 sccm SiH<sub>4</sub> flow for the intrinsic layer;
- 2) 10 sccm PH<sub>3</sub> and 40 sccm SiH<sub>4</sub> for the n-type layer;
- 3) 6 sccm B<sub>2</sub>H<sub>6</sub> and 40 sccm SiH<sub>4</sub> for the p-type layer.

On the front side of the wafer we have deposited a 5 nm thick intrinsic a-Si:H buffer layer, and 10 nm thick n-type doped a-Si:H. On the rear we have deposited 5 nm thick intrinsic a-Si:H followed by a 15 nm thick p-type doped a-Si:H layer and a  $\delta n$  doped a-Si:H buffer layer. Afterwards we have evaporated and subsequently removed 30 nm thick chromium layer on both sides of the device to form the high conductivity CrSi layer. By sputtering system we have deposited the ITO layers, 67 nm at the emitter side and 80 nm at the back side, using the following conditions: ITO target, 25 sccm Ar, 5 sccm O<sub>2</sub>, 150 °C, 200 W RF power. Finally, by e-beam evaporator, we have deposited 2  $\mu$ m of Al on the whole surface of the cell, as back contact, and 2  $\mu$ m of silver (Ag) through a grid shape mask, as front metal grid. The total area of the device has been fixed at 4 cm<sup>2</sup>.

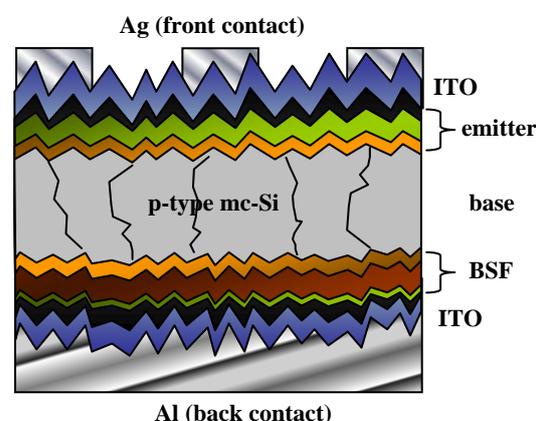


Figure 2: Basic structure of our double heterostructure solar cell (not to scale).

### 4 RESULTS AND DISCUSSION

The PV devices have been characterized by current voltage (I-V) measurements at standard conditions (100 mW/cm<sup>2</sup>, AM1.5G and 25 °C), and by quantum efficiency (QE) in the range of 350-1200 nm. In Figure 3 the lighted I-V characteristic of the heterostructure solar cell is reported together with the evaluation of its photovoltaic parameters.

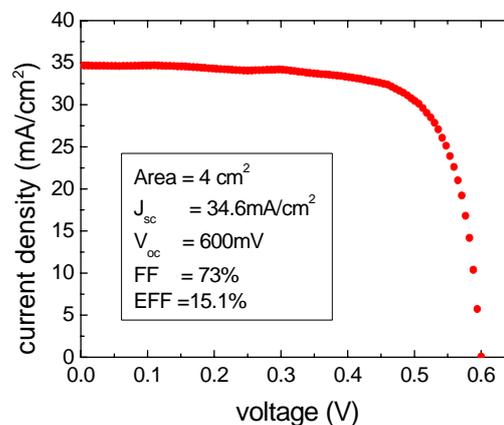


Figure 3: I-V characteristic under standard conditions (100 mW/cm<sup>2</sup>, AM1.5G and 25 °C) and photovoltaic

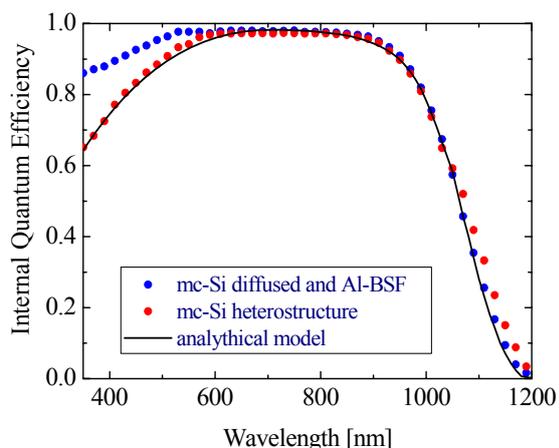
parameters of the double heterostructure solar cell based on p-type mc-Si wafers.

The photovoltaic efficiency of this cell is still lower than that of the industrial high efficiency P-diffused and Al-BSF cell (15% vs. 17%). The fill factor and the series resistance are still the limiting factors; although the chromium silicide formation on the top of the amorphous films results in a series resistance reduction and a better charge collection.

The shunt resistance is strongly influencing the open circuit voltage. To prove this we have fabricated a sister wafer following the same process but chemically polishing, instead of alkaline texturing, the surfaces. The measured  $V_{oc}$  increased 30 mV (from 600 mV to 630 mV). This means that the thickness uniformity of the thin amorphous layers over a wide and textured silicon surface still requires further investigations.

Up to now just SANYO [3] has been able to produce high photovoltaic efficiency on 100 cm<sup>2</sup> substrate. All other research groups have obtained good results only on very small device.

Even if the obtained photovoltaic efficiency is not impressive, it is worth to note that this result is one of the very few results obtained on a-Si:H/c-Si heterostructure based on p-type textured multi-crystalline silicon wafer, and the best published up to now.



**Figure 4:** Internal Quantum Efficiency comparison of our heterostructure device (red symbols) and P-diffused + Al-BSF solar cell (blue symbols) based on sister p-type mc-Si substrate. The line is the fit with an analytical model of the IQE data of the heterostructure cell.

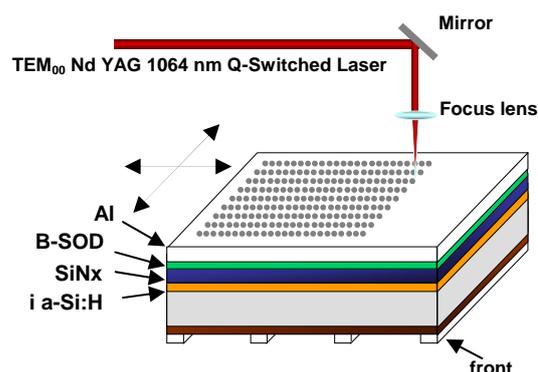
In Figure 4 the Internal Quantum Efficiency (IQE) data of the heterostructure solar cell are reported (red symbols) together with the simulation obtained by a simple analytical model (black line). This model takes into account the absorption coefficients ( $\alpha(\lambda)$ ), the thickness of the materials, the depletion width, and the diffusion length in the crystalline silicon bulk. Of course, the photocurrent is as a sum of the two main components: drift at the depletion region and diffusion in the bulk. The carrier transport at the a-Si:H/c-Si interface, limited by the defect density, is restricted by the  $\mu\tau$  product of the amorphous silicon, that has been fixed at 10<sup>-12</sup> [cm<sup>2</sup>/V]. By fitting procedure in the blue region of the spectrum this simple model is able to verify the thicknesses of the

amorphous silicon layers not easy to control, since they are very thin. Indeed we have found that the n-type a-Si:H is 8 nm and the intrinsic a-Si:H is 5 nm. The value of the effective diffusion length of the minority carriers has been obtained by the linear behavior of the IQE vs  $\alpha_{c-Si}(\lambda)$  at the edge of the silicon bandgap absorption and has been evaluated as 350  $\mu$ m. Tunneling effect and other series resistance losses are not considered.

In the Figure 4 are also showed the IQE data (blue symbols) of the industrial high efficiency solar cell realized by a standard high temperature process (P-diffused and Al-BSF) using a sister substrate and having an efficiency of 17%.

In the blue region of the spectrum the IQE of the diffused cell is higher than one of the heterostructure. Even if the thicknesses of the amorphous silicon layers are very thin, their absorption represents a limiting factor. One way to improve the blue response is to optimize the front transparent conductive oxide (TCO) layer characteristics, like increasing its transparency and its conductance.

Since in the spectrum region between 900 nm and 1000 nm the IQE of both cells is almost equal we can assume an equal effective diffusion length ( $L_n$ ). It is worth to note that the back contact of the diffused cell is ensured by the high temperature Al diffusion, able to produce a gettering of the bulk impurities and an effective surface field as well. Then we can deduce that also the heterostructure device has a similar effect. Probably the intrinsic a-Si:H layer is able to passivate the back side of the silicon wafer and the p-type a-Si:H/CrSi/ITO stuck layers are able to promote a good extraction of holes. Moreover the heterostructure device presents a quite higher internal reflectance, as evident comparing the IQE of both cells in the spectrum region between 1050 nm and 1200 nm. This means that the mirroring effect of the a-Si:H/ITO/Al structure deposited on a textured surface is better than that of Si/Si-Al-alloy/Al.

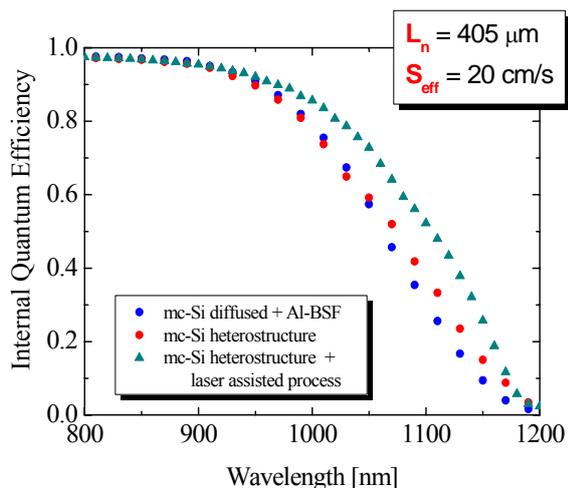


**Figure 5:** Basic structure of our alternative heterostructure solar cell having a SHJ as emitter and at the back the stuck layers: (intrinsic a-Si:H/SiNx/B-SOD/Al) + processed by laser to get the localized BSF (not to scale).

To increase the holes collection at the back metal contact a thickness reduction of the deposited a-Si:H layer at the rear is needed together with a reduction of the activation energy of the p-type doped a-Si:H layer. The

application of CrSi layer at the back side of the cell before the ITO deposition goes in this direction and can also reduce the contact resistance between the p-type doped a-Si:H and the ITO layers.

To further increase the infrared response of our device we are investigating a new back side scheme (see Figure 5) that replaces the rear heterostructure with the following stack layers: intrinsic a-Si:H/SiNx/B-SOD/Al. After the deposition of these layers the rear side has been treated by a laser assisted process to get localized back surface field [11]. The results in terms of IQE are showed in the Figure 6.



**Figure 6:** Internal Quantum Efficiency data comparison of the double heterostructure device (red symbols), of the P-diffused + Al-BSF solar cell (blue symbols), and of the solar cell having a SHJ as emitter and the stuck layers intrinsic a-Si:H/SiNx/B-SOD/Al + laser assisted process at the back. The devices are based on sister p-type mc-Si substrates.

The first obtained results are very good in terms of  $L_n$  (from 350  $\mu\text{m}$  to 450  $\mu\text{m}$ ), and  $J_{sc}$  (an increase of about 4  $\text{mA}/\text{cm}^2$ ). The  $S_{eff}$  at the back has been evaluated as 20  $\text{cm/s}$ , but there is enough room to improve this parameter by optimizing the surface pre-treatment prior the amorphous silicon deposition. Finally it is worth to point out that the entire process still remains performed at low temperature.

## 5 CONCLUSION

We have fabricated double amorphous /crystalline silicon heterojunction solar cell on 1  $\Omega\cdot\text{cm}$  p-type alkaline textured multi-crystalline substrate with 15% efficiency. In order to increase the hole and the electron collection, respectively, at the back side and at the front side of the cell; we have deposited a chromium silicide film between the amorphous silicon and the transparent conductive oxide layers. The role of this buffer layer has been detailed investigated. We have discussed the transport mechanism at the rear side of the device by modeling the heterostructure device. Even if the PV performances we have got are still below that one obtained by using the high temperature technology (15% vs. 17%); it is worth to note that is the best published

result on multi-crystalline silicon HIT structure up to now. Finally we have introduced a new promising low temperature design for SHJ solar cells based on p-type mc-Si wafers, having an a-Si:H/c-Si heterostructure as emitter and a stuck layer of intrinsic a-Si:H/SiNx/B-SOD/Al at the rear of the device, followed by a laser assisted process to get localized back surface field.

## 6 ACKNOWLEDGEMENTS

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