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Front side recombination losses analysis in rear emitter silicon heterojunction solar cells

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Abstract

Rear emitter silicon heterojunction solar cells are attractive because of the lateral conductivity of electrons through the wafer yielding a higher fill factor than conventional front emitter structures. However, minority carriers being collected at the rear of the cell, they are more sensitive to recombination at the front interface. In this paper we present a detailed analysis of recombination losses impacting the short-circuit current; the roles of the (i)*a*-Si:H buffer layer and of the (n)*a*-Si:H layers are identified thanks to variation of their thicknesses. We point out the critical role played by both bulk *a*-Si:H absorption and recombination, as well as the field effect induced by the (n)*a*-Si:H layer.

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Keywords: Heterojunction; quantum efficiency; rear emitter; recombination

1. Introduction

Silicon heterojunction solar cells are of great interest due to their high open-circuit voltage potential achievable thanks to passivation of the crystalline silicon substrate with hydrogenated amorphous silicon. Recently a power conversion efficiency of 24.7% was reached, with an outstanding fill factor of more than 83% [1].

Such high fill factors could be obtained with rear emitter structures. Indeed, on n-type wafers, photo-generated electrons can benefit from the high lateral conductivity to be extracted towards the contacts [2]. However, holes photo-generated on the front side have to travel through the whole substrate to be extracted at the rear of the cell.

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Thus they are more subject to recombination at the front interface and in bulk *c*-Si, which could have a negative impact on the short-circuit current, as in rear contacted solar cells [3]. Therefore a detailed analysis of recombination losses in such rear emitter structures is necessary to enlighten weak points and optimize solar cells at best. In particular it is essential to quantify losses due to parasitic absorption in front (i+n)*a*-Si:H stacks and losses due to front interface recombination. In this context we present a comprehensive study of recombination losses in rear emitter silicon heterojunction solar cells based on experimental results and optical and electrical simulation. In section 2, experimental and simulation procedures are explained. In section 3, quantum efficiency and effective minority carrier lifetime measurements are introduced. Finally section 4 presents a discussion based on the comparison of quantum efficiency measurements and optical modeling.

2. Experimental and simulation

2.1. Samples processing

In this paper we present characterization of samples including complete cells on pre-industrial size (10x10 cm^2) wafers and cell precursors. All depositions were made in a semi-industrial cluster tool including a load-lock, transfer chambers, two RF plasma enhanced chemical vapor deposition (PECVD - for amorphous silicon layers) chambers and two physical vapor deposition (PVD – for indium tin oxide and silver metallization) chambers. More details on deposition conditions can be found in reference [4].

Full cells were made on n type, 12.5x12.5 cm^2 high quality FZ textured wafers. Before *a*-Si:H deposition, they were cleaned and received an hydrofluoric acid treatment to remove the native oxide and passivate the surface with H atoms. The front and back *a*-Si:H stacks ((i)+(n)*a*-Si:H and (i)+(p)*a*-Si:H respectively) were deposited in PECVD chambers with high reproducibility. The thickness of (i)*a*-Si:H and (n)*a*-Si:H layers were varied to change the amount of light absorbed by the front stack and the *a*-Si:H/*c*-Si interface quality. Then front and back indium tin oxide (ITO) layers were sputtered on amorphous stacks. To complete cells, the back side was completely covered with silver, while front metallization was screen-printed. Finally, 10 x 10 cm^2 cells were isolated with a laser. The spectral response and reflectivity of complete cells are measured using commercial setups.

In order to get access to individual layer parameters, such as thicknesses, optical properties, conductivity, etc., individual layers or stacks were deposited on polished *c*-Si or glass substrates placed in deposition chambers during cell processing. Each sample has a particular design adapted to the characterization technique it is intended for: spectral ellipsometry, spectrophotometer, effective minority carrier lifetime (Sinton setup [5]).

2.2. Front side optical simulation

In order to fully interpret spectral response measurements on full cells, it is necessary to simulate the optical behavior of complete solar cells. From spectral ellipsometry measurements on individual layers, we extracted optical constants and thicknesses for *a*-Si:H and ITO layers. These data were loaded in a homemade transfer matrix based optical simulation program that was validated by comparison with the freeware OPAL [6]. Individual layers were stacked up to recreate fabricated samples which were measured with a spectrophotometer. In this way, absorption, reflection and transmission could be compared. This procedure, repeated for all stacks on several substrates, allowed us to validate our model to simulate full cells. In figure 1, we show an example of the simulated absorptions in the different layers, together with the absorption measurement of the full cell. Data are shown up to a wavelength of 700 nm which is the limit where the back side does not come into play. First of all, it is worth noticing that the experimental curve is well reproduced with our simulation: the error is less than 3% absolute. This indicates that the whole simulation chain - test samples preparation, spectral ellipsometry measurements and treatments, optical simulation - is valid. In addition, this simulation tools gives us a way to access the absorption in each layer. Assuming that each absorbed photon gives rise to an electron-hole pair, this allows us to quantify photo-generation in each layer, which will be the basis of spectral response interpretation in the next section.

With confidence in our method, we were able to simulate our cells with different front *a*-Si:H layers thicknesses. Results will be used in sections 3 and 4, where the role of these layers played on the spectral response and thus on the short circuit current is analyzed.

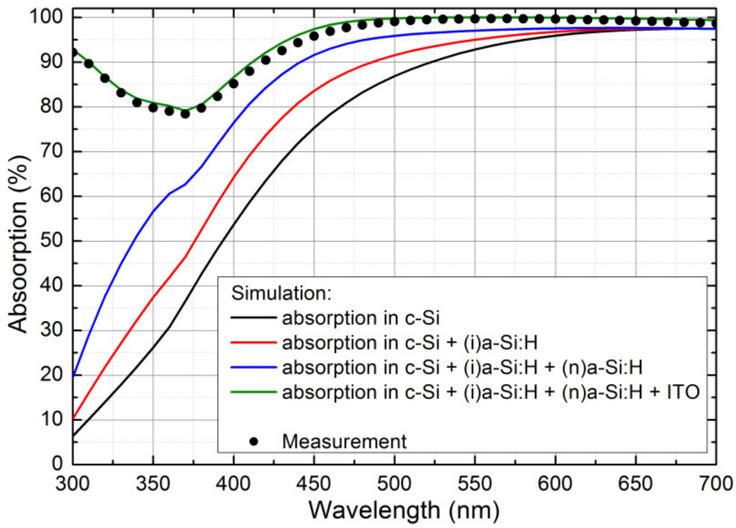

Fig. 1. Measured and simulated light absorption for the sample with 7 nm (i)*a*-Si:H layer and 7 nm (n)*a*-Si:H layer.

3. Recombination losses estimation

In this section our objective is to present the way IQE measurements are analyzed to shed light on the role played by the front amorphous silicon stack on the short circuit current. As an approximation we will consider that the front stack affects only the current generated from short wavelengths, up to 700 nm, at least as far as light absorption is concerned. In reference [7], Holman showed that light absorbed in the front ITO layer generates no electrical current. We will rely on this result, and start from the hypothesis that, a priori, all light absorbed up to 700 nm could lead to an electrical current, except the part caught by the ITO layer. In this way the concept of 'parasitic absorption' is reserved for light absorbed in ITO. For *a*-Si:H and *c*-Si we will investigate the balance between electron-hole pairs generation and recombination. Generation in each layer can be well estimated with the help of the optical simulation tool. On the contrary it is more challenging to track recombination because several paths come into play. Assuming that bulk *c*-Si is of high quality, three main ways for the carriers to recombine remain: at the (i)*a*-Si:H/(n)*c*-Si interface, within the front (i)*a*-Si:H layer or within the (n)*a*-Si:H layer. A hypothetical recombination path at the (n)*a*-Si:H/ITO interface is included in the bulk (n)*a*-Si:H recombination for simplicity, which won't change the overall conclusions.

In Figure 2, we show the Internal Quantum Efficiency (IQE) measurement and simulated charge carriers photo-generation in *c*-Si, and in *c*-Si and *a*-Si:H, for the sample with a 4.5 nm thin (n)*a*-Si:H layer and 4.4 nm thin (i)*a*-Si:H layer.

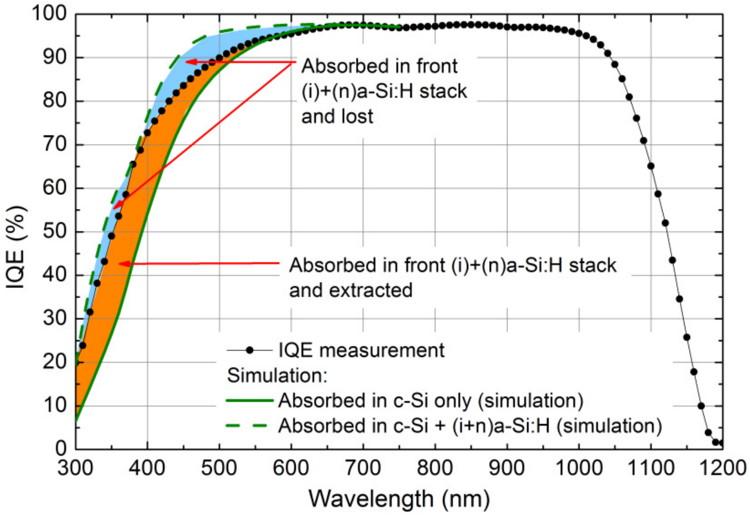

Fig. 2. Internal quantum efficiency (IQE) and optical simulation of the absorption for the sample with 4.6 nm (i)*a*-Si:H layer and 4.5 nm (n)*a*-Si:H layer.

We assume first that all photons absorbed in the front (i+n)*a*-Si:H stack plus in *c*-Si could a priori lead to the extraction of one electron-hole pair; in this case, the IQE would coincide with the outer green dashed curve. The measurement shows that this is not the case as the black points curve is below this green dashed curve. Everything that is between these two curves represent losses by recombination in (n)*a*-Si:H, in (i)*a*-Si:H or at the (i)*a*-Si:H/(n)*c*-Si interface. However one notices that the IQE is above the curve representing light absorbed in *c*-Si only, meaning that a significant part of the current generated in (i+n)*a*-Si:H can be extracted.

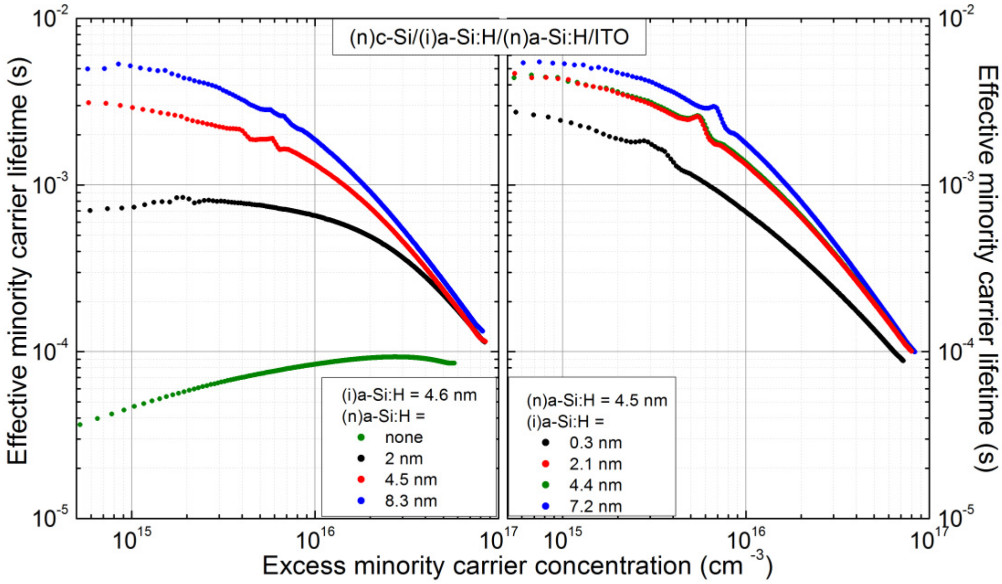

Fig. 3. Minority carrier lifetime measurements (Sinton photoconductance setup) for samples passivated with different (n+i)*a*-Si:H stacks.

In addition, we measured the minority carrier effective lifetime limited by the (i+n)a-Si:H stacks under study. Results are shown in figure 3. For varying thicknesses of the (n)a-Si:H layer (figure 3 left hand side), the low injection region is at first severely impacted, whereas variation of the (i)a-Si:H layer thickness (figure 3 right hand side) leads to a more or less parallel shift of the curves. This is well consistent with works of Leendertz on passivation mechanisms in silicon heterojunctions [8]. We notice here in particular that a too thin (n)a-Si:H layer results in a dramatic decrease of the lifetime, especially at low injection levels where short-circuit condition operates: a high field effect passivation is necessary to maintain a high minority carrier effective lifetime.

Both IQE and lifetime measurements are used in the next section to provide an analysis of recombination losses at the front side.

4. Discussion

In figure 4 we show IQE measurements and optical simulations of all samples up to 700 nm. As in figure 3, figure 4a presents results for a fixed (i)a-Si:H layer and varying (n)a-Si:H layers, whereas figure 4b shows results for a fixed (n)a-Si:H layer and varying (i)a-Si:H layers. First of all, it is worth noticing that absorption in c-Si +(i+n)a-Si:H is the same for all samples, as it amounts $1 - R - A_{ITO}$ where R is the reflectivity and A_{ITO} is the absorption in the ITO. Then in (b), the absorption in c-Si+(i)a-Si:H does not change as it amounts $1 - R - A_{ITO} - A_{(n)a-Si:H}$ where the (n)a-Si:H layer is the same for the four samples.

Now, from figure 4(b), in the light of the previous section's analysis, we can affirm that almost all the light absorbed by the a-Si:H stack for wavelength below 400 nm is extracted. Although a slight decrease of the IQE is observed as the (i)a-Si:H layer thickness increases, this results contracts with findings of Holman, who saw that no current can be extracted from the photo-generation in the (p)a-Si:H in front emitter solar cells [7]. For the same wavelength range in figure 4(a), the same decrease of the IQE for increasing (n)a-Si:H thickness occurs, except that it is much more dramatic for the thickest (n)a-Si:H layer. These trends can be explained by the longer path minority charge carriers photo-generated close to the (n)a-Si:H surface have to travel through. The chance for them to recombine is increased, especially when the a-Si:H stack thickening is due to the more defective (n)a-Si:H layer, for which a typical diffusion length value is around 5 nm.

Next, for wavelengths above 600 nm, no difference in the IQE of samples with different (i)a-Si:H thicknesses is noticeable. This can be attributed to minority carrier effective lifetime which remains high for all these samples (see figure 3). However the sample with 2 nm thin (n)a-Si:H layer in figure 4(a) has a lower IQE than other samples above 600 nm (difference actually starting at 500 nm, and going up to 1000 nm). This is due to the low lifetime at low injection level: the field effect passivation is not acting anymore because the doped layer is too thin [8]. As an extreme case, samples without (n)a-Si:H layers could extract only 3 mA cm^{-2} (not shown here). This finding also differs from what occurs generally on front emitter structures where the short circuit current degrades far less than the fill factor or the open circuit voltage with respect to front interface defect density [9]. Here the current has to be considered as sensitive as other cell parameters. Furthermore, it has to be outlined that the (n)a-Si:H/(n)c-Si interface has only a small effect on the short circuit current on front emitter structures [4]; thus the (n)a-Si:H/(n)c-Si interface has a dramatic influence only when placed on the front side.

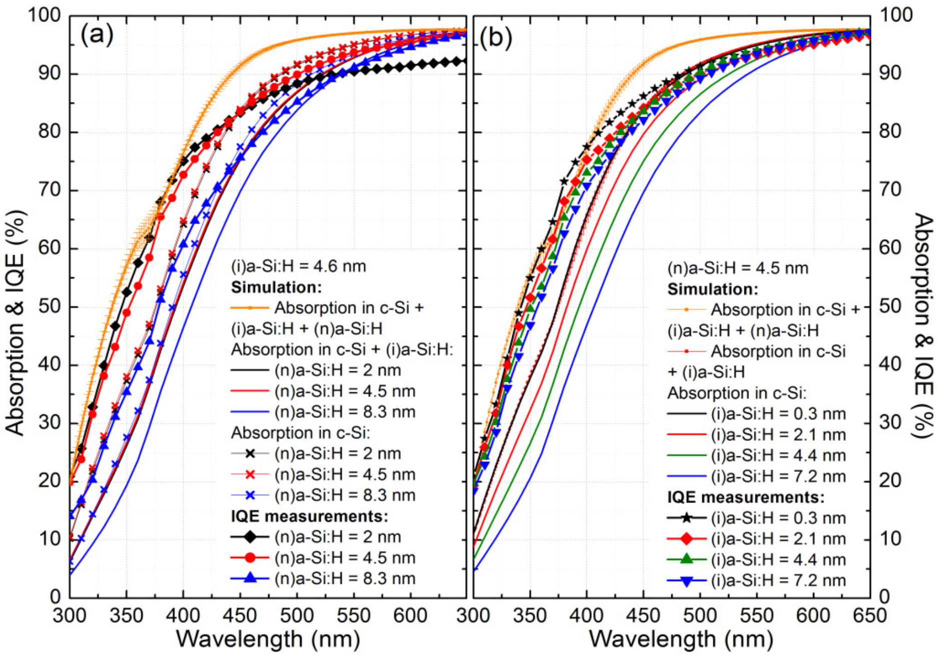

Fig. 4. IQE measurement and absorption simulation for all samples investigated in this study. (a) Variation of the (n)*a*-Si:H layer thickness ; (b) Variation of the (i)*a*-Si:H layer thickness.

Then, from 400 nm to 600 nm the part of photo-current generated in *a*-Si:H and extracted decreases. More precisely, when the (n)*a*-Si:H layer is thick enough to maintain a high minority carrier lifetime, but thin enough not to absorb excessively, almost all light absorbed in (i)*a*-Si:H seems to be converted in extracted carriers. On the contrary, photons absorbed in the (n)*a*-Si:H layer seem to be progressively lost as their wavelength increases. Moreover, as the (n)*a*-Si:H layer becomes too thick, light absorbed in (i)*a*-Si:H is in a greater part lost. Several causes could give an explanation to these observations (see figure 5 for helpful indicative sketches). *(a)* First some light absorbed in *a*-Si:H does not give rise to an electron-hole pair: this might be the case when transitions between delocalized states (conduction or valence bands) and localized states (band tail and deep defects) are involved. Therefore this effect would be stronger for doped layers as they are more defective. However this hypothesis is the least plausible because absorption by defects is generally weak and energies do not correspond with a band gap of about 1.7 eV. *(b)* A second reason involves the fact that charge carriers generated at higher energies through the absorption of a high energy photon may benefit from the thermal relaxation time in delocalized states to be extracted towards each side of the *a*-Si:H stack. As the photon wavelength increases, photo-generated carriers have less energy and might recombine faster. *(c)* A third cause might be related to charge transport from *a*-Si:H to the ITO once generated. Carrier photo-generated close to the (n)*a*-Si:H interface, i.e. from short wavelength), would have a higher tunneling rate to be emitted to the ITO because they “see” a lower barrier than carriers coming from deep into the *a*-Si:H stack.

The authors didn’t find relevant contributions in the literature to strengthen one of these explanations which remain at the hypothesis stage. More work is necessary to track the dynamic of charge carriers after photo-generation.

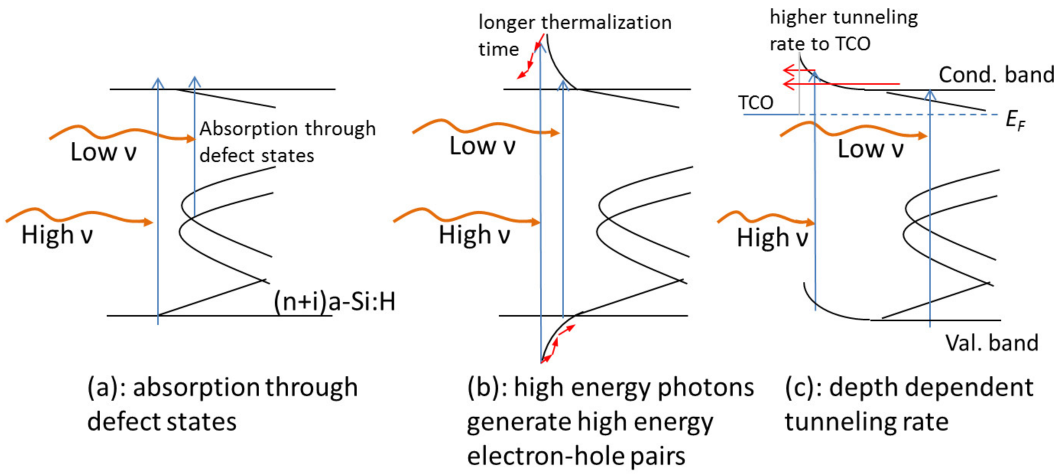

Fig. 5. Hypothesis for the depth dependent extraction of carriers photo-generated in (n)*a*-Si:H.

5. Conclusion

In this paper we present a comprehensive analysis of recombination-induced losses at the front of rear emitter silicon heterojunction solar cells. Contrary to front emitter cells, the photo-current is more sensitive to recombination at the (n+i)*a*-Si:H/(n)*c*-Si interface as there is no p-n junction induced electric field to separate charges. Therefore, when the (n)*a*-Si:H layer becomes too thin, there is no field effect passivation anymore and the interface is highly recombinative. We also showed that almost all charge carriers photo-generated in (i)*a*-Si:H can be extracted, provided the (i)*a*-Si:H is not too thick. Some light absorbed in the (n)*a*-Si:H layers also generates a current but also some losses, depending on the thickness of the *a*-Si:H stack. Main losses occur for wavelengths between 400 nm and 600 nm. This opens new routes for front side electron collector optimization. Further analysis of the role of the front side on fill factors will be presented in an upcoming publication.

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