PROGRESS IN CONTACTING a-Si:H/c-Si HETEROJUNCTION SOLAR CELLS AND ITS APPLICATION TO INTERDIGITATED BACK CONTACT STRUCTURE

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ABSTRACT: This work presents our progress in designing the rear emitter of a-Si:H / c-Si (n) heterojunctions solar cells (Si-HJ). We study the emitter saturation current density (J_{0e}) of p-type a-Si:H layers and show that it greatly depends on the layer thickness and conductivity. Different p-type a-Si:H emitters are tested experimentally on Rear Emitter (RE) as well as Interdigitated Back Contact (IBC) Si-HJ devices. A low conductivity (1.4×10^{-6} $S.cm^{-1}$) layer allows the better V_{oc} values about 650 mV but causes resistive losses on both types of solar cells. For the IBC devices, a low emitter contact fraction induces not only fill factor (FF) losses but also a decrease of the short circuit current (J_{sc}) value. By optimizing the rear side geometry an efficiency of 12.7% is achieved for the Si-HJ IBC structure on 25 cm^2 n-type substrate.

Keywords: Silicon solar cells, Heterojunctions, Back contact

1 INTRODUCTION

Interdigitated Back Contact (IBC) solar cells efficiency could be in theory improved through better contact passivation, i.e. using a-Si:H/c-Si heterojunctions (Si-HJ) [1]. However, experimental results for the Si-HJ IBC structure are up to now limited because of a high series resistance due to different contributions. A low a-Si:H conductivity [2][3], a high interface defects density and contact resistivity [4] can for example partly explain the low fill factor values obtained on Si-HJ IBC cells. We focus in this study on the different ways to enhance IBC Si-HJ efficiency by working on the p-type a-Si:H emitter layer and its contacting scheme.

No rear intrinsic a-Si:H buffer layer is here used since it can induce resistive losses on IBC Si-HJ cells and limit their fill factor values below 60 % [2][3]. Without using this buffer layer, higher FF values above 70 % can indeed be obtained [2][4]. We first study the influence of p-type a-Si:H layers conductivity and thickness on their J_{0e} value. Different layers are then applied on 25 cm^2 Rear Emitter (RE) and Interdigitated Back Contact (IBC) Si-HJ cells on planar 2-5 Ω.cm n-type FZ c-Si (Figure 1).

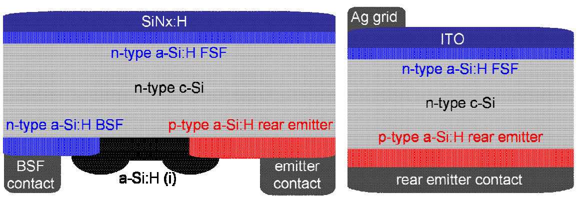

Figure 1. Sketches of the IBC Si-HJ (Left) and the RE Si-HJ (Right) solar cells

IBC Si-HJ cells are processed with thin patterned metallic masks (MM) to localize the different rear layers [5]. On these devices the impact of emitter doping and contact fraction on this structure is tested both experimentally and by means of modelling. 300 µm thick n-type FZ (100) oriented silicon wafers with a high bulk quality are used in this work. They are polished with a 100 mm diameter and 1-5 Ω.cm resistivity. The native oxide removal before a-Si:H deposition is achieved by a 30 s dip in buffered HF without further rinse. LASER scribing is used at the end of the process to separate 25 cm^2 cells from the four inches wafers.

2 REAR EMITTER STACK OPTIMIZATION ON SILICON HETEROJUNCTION CELLS

2.1 Emitter Saturation Current Density (J_{0e})

To obtain high V_{oc} value, an emitter layer has to achieve a low emitter saturation current density. Different p-type a-Si:H layers with increasing doping gas flow are deposited in a Plasma Enhanced Chemical Vapor Deposition (PECVD) 13.56 MHz RF reactor at 200°C. By varying the doping gas flow, we obtain p-type a-Si:H layers with different dark conductivity values. We deposit 27+/-2 nm of these p-type a-Si:H layers on both sides of the c-Si wafers. The J_{0e} values are measured through the use of effective lifetime measurements carried with a Sinton WCT-100 tool [6]. Figure 2 shows the influence of p-type a-Si:H conductivity on its J_{0e}.

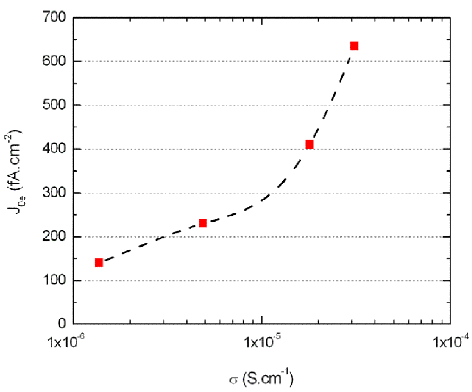

Figure 2. Measured J_{0e} values for p-type a-Si:H emitters having different dark conductivity values

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Our results clearly show that the J_{0e} value depends on the p-type a-Si:H conductivity. The lowest J_{0e} value of 140 $fA.cm^{-2}$ is obtained for the less conductive material ($1.4x10^{-6}$ $S.cm^{-1}$). However, for “device quality” p-type a-Si:H layers, a conductivity value of $1x10^{-5}$ $S.cm^{-1}$ seems to be necessary [7]. For the material with a conductivity of $1.8x10^{-5}$ $S.cm^{-1}$ a higher J_{0e} value of 410 $fA.cm^{-2}$ is obtained. A higher p-type a-Si:H conductivity probably induces more active dopants, but also more defects in the emitter layer and at the a-Si:H / c-Si interface. Two different B-doped a-Si:H materials with either low [L] ($1.4x10^{-6}$ $S.cm^{-1}$) or high [H] ($1.8x10^{-5}$ $S.cm^{-1}$) conductivity value are chosen to study the impact of the emitter thickness on its J_{0e} value (Figure 3).

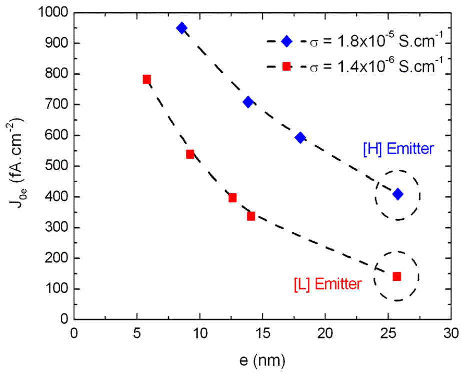

Figure 3. Influence of p-type a-Si:H layer thickness on the emitter saturation current density for two different conductivity values.

The use of a thick p-type a-Si:H layer is shown to reduce emitter recombination and therefore decrease the J_{0e} value. This can be attributed to structural relaxation in the deposited a-Si:H with increasing layer thickness [8]. The thickest [L] and [H] layers are therefore used to fabricate 25 cm^2 Rear Emitter Si-HJ cells.

2.2 Rear Emitter Si-HJ solar cells

On RE Si-HJ cells, a 25 nm thick n-type a-Si:H layer is also deposited at the front to form a Front Surface Field (FSF). This FSF is covered by an 80 nm thick sputtered ITO layer onto which an Ag grid is screen-printed. The p-type a-Si:H emitters are deposited at the rear side and covered by a 1 µm thick sputtered Al layer.

AM1.5 J-V curves measured for RE Si-HJ cells having a [H] and a [L] emitter are shown on Figure 4. Low J_{sc} values are obtained for our RE Si-HJ cells due to light absorption in the 25 nm n-type a-Si:H front surface field layer. Accordingly to J_{0e} measurements, the use of [L] emitters allows a 16 mV higher V_{oc} value compared to the more conductive material. This better emitter quality also enhances the J_{sc} value about 1 $mA.cm^{-2}$. The drawback of such [L] emitters comes from their poor contact properties revealed by a low FF value. An s-shaped J-V curve is indeed obtained for [L] emitters probably due to a Schottky barrier at the Al / a-Si:H interface. Al shows a low workfunction value about 4.3 eV [9]. This is far from the 5.3 eV value which is necessary to achieve flat band conditions and avoid depletion in the p-type a-Si:H emitter layer [10]. This barrier disappears when using [H] emitters and high FF of about 78% are obtained. The higher a-Si:H doping makes probably tunnelling mechanisms dominate at the semi-conductor/metal interface so that the charge carriers are less influenced by the Schottky barrier [11].

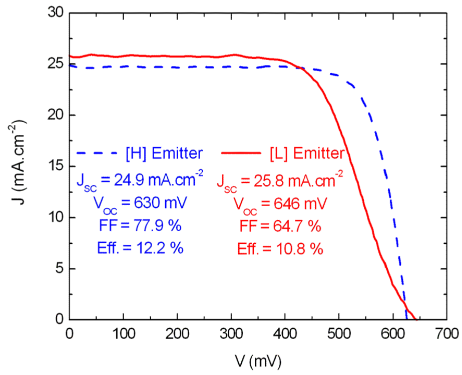

Figure 4. AM1.5 J-V curves of RE Si-HJ cells - Influence of p-type a-Si:H emitter conductivity

3 FABRICATION AND OPTIMIZATION OF IBC SILICON HETEROJUNCTION SOLAR CELLS

3.1 Influence of the a-Si:H emitter conductivity

The IBC Si-HJ cell structure comprises a 8 nm n-type a-Si:H (n) / 80 nm SiN_x:H stack as front side anti-reflective coating. The rear side geometry consists in interdigitated comb-shaped p-type a-Si:H emitter and n-type a-Si:H Back Surface field (BSF) zones separated by a 40 nm thick a-Si:H (i) layer. The emitter contact is made of 3 µm Al layer whereas a stack of 80 nm ITO and 3 µm Al is used for the BSF contact. Our IBC Si-HJ cell geometry implies the alignment of different layers, so that experimentally the emitter and BSF layers are partly contacted. That is the reason why in our simple cell geometry (Figure 1) only 64% of the p-type a-Si:H emitter and 33% of the n-type a-Si:H BSF is contacted. We note “F_{Em}” the emitter contact fraction which represents the ratio between the a-Si:H emitter width (700 µm) and its contact width (450 to 650µm). We fabricated 25 cm^2 IBC Si-HJ cells with the previously developed [H] and [L] emitters and measure their AM1.5 J-V curves. The results are shown on Figure 5.

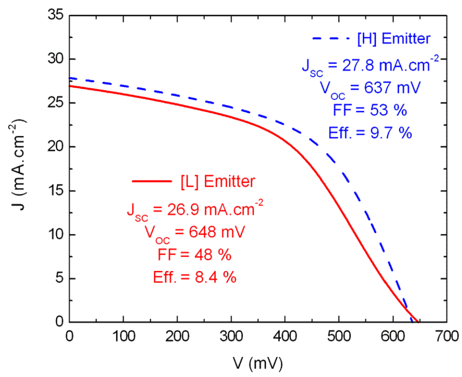

Figure 5. AM1.5 J-V curves of IBC Si-HJ cells - Influence of p-type a-Si:H emitter conductivity - An emitter contact fraction of 0.64 is used for both structures

With both kinds of emitters, efficiency values below 10% are obtained mainly due to the poor FF values. IBC Si-HJ cells with [L] emitter reach a V_{oc} next to 650 mV whereas a slightly lower value is obtained with a [H] one. As for RE cells, a better FF is obtained on a [H] emitter (53%) compared to a [L] one (48%) due to an s-shaped J-V curve. Both [H] and [L] emitters induce a current decrease at low bias on the AM1.5 J-V curves. According to the double diode model, this can be attributed to a low parallel resistance (R_P) of the devices. However the pseudo J-V curve of the fabricated cells obtained by SunsV_{oc} measurements [12] show pseudo-FF values above 80%. This indicates that our devices show a high R_P value and are therefore not shunted. The J_{sc} values are slightly higher than those previously obtained with RE cells because of a thinner FSF layer and the lower front reflectance (no Ag grid). We observe on these IBC cells an opposite trend compared to RE devices. Here, a higher J_{sc} value is obtained with the [H] emitter compared to the [L] one. This result and the unusual J-V curve behaviour ("shunted-like") can be explained through the use of two dimensional modelling.

3.2 Two dimensional modeling of IBC Si-HJ cells

Based on previous work [13][14], the ATLAS software from Silvaco International is here used to study the influence of IBC Si-HJ cells emitter design on their AM1.5 J-V curves. As shown in Figure 6 the emitter doping level (D) and its contact fraction (F_{Em}) have a great influence on the modeled IBC Si-HJ cells J-V curves behaviour.

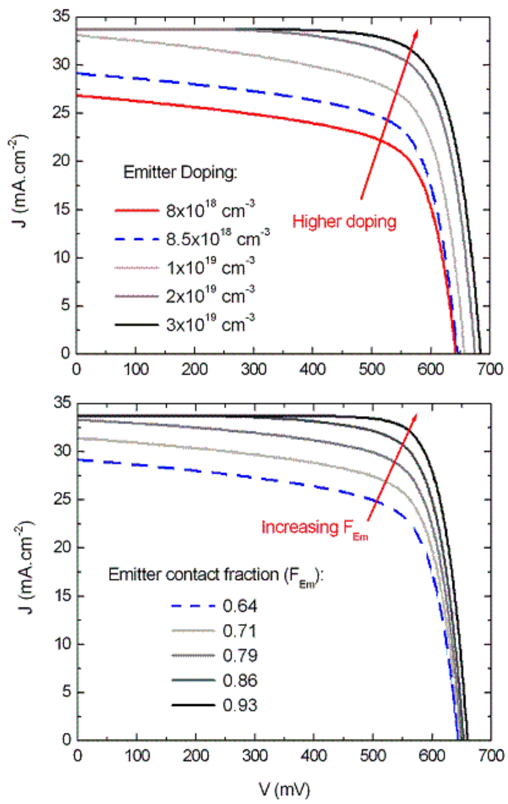

Figure 6. Simulated AM1.5 J-V curves of IBC Si-HJ solar cells with (a) variable emitter doping (Constant F_{Em} = 0.64) and (b) variable contact fraction (Constant Doping = 8.5x10^{15} cm^{-3})

The modeled structures consist in a 300 µm thick n-type c-Si substrate (1 ms bulk lifetime and 2e15 cm^{-3} base doping) with a 80 nm antireflective coating having a refractive index of n=2.05 at the front side. The rear side consists in a 700 µm wide p-type a-Si:H emitter and 375 µm wide n-type a-Si:H BSF separated by 100 µm intrinsic a-Si:H in agreement with experimental data. Both base and emitter electrodes are modelled by an ohmic contact covering a fraction of the doped a-Si:H layers.

Figure 6(a) shows the influence of the emitter doping level (D) for a constant F_{Em} of 0.64. For clarity, a low defects density of 1x10^{10} cm^{-3} is here assumed at the p-type a-Si:H / c-Si interface for all doping levels although it should actually depend on the a-Si:H doping. In the simulation a higher doping means therefore a higher V_{oc} value due to higher junction potential. Through these modelling results, we can approximate the doping of [H] and [L] emitters to be between 8x10^{18} cm^{-3} and 8.5x10^{18} cm^{-3}. This confirms that IBC Si-HJ cell having a F_{Em} of 0.64 obtain a lower J_{sc} with [L] emitter than with a [H] one. The opposite trend can be seen experimentally on RE cells. For an emitter doping level above 1x10^{19} cm^{-3} an increase of D induces a higher FF value. Below 1x10^{19} cm^{-3} a decrease of D does not lead to further FF decrease but lowers the J_{sc} value. The same trends appear on Figure 6(b) concerning the influence of F_{Em}. By decreasing the F_{Em} value from 0.93 to 0.79 the FF value drops due to the "shunted-like" behaviour. Below the value of 0.79 a smaller emitter contact fraction does not change the FF value but lowers the J_{sc}. By comparing these simulation results with our experimental trends, two main findings appear:

1/The "shunted-like" J-V curve behaviour can be explained by a low F_{Em} value and/or a low doping level.

2/The emitter design (D and F_{Em}) has a great impact on FF as well as J_{sc} values.

A physical explanation for this phenomenon will be published elsewhere [15].

3.3 Influence of the emitter contact fraction

Experimentally better emitter conductivity means a higher J_{0e} value. We therefore tested experimentally an increase of the emitter contact fraction from 0.64 to 0.79 to enhance IBC Si-HJ cells efficiency. The AM1.5 J-V curves of these IBC Si-HJ cells are shown on Figure 7.

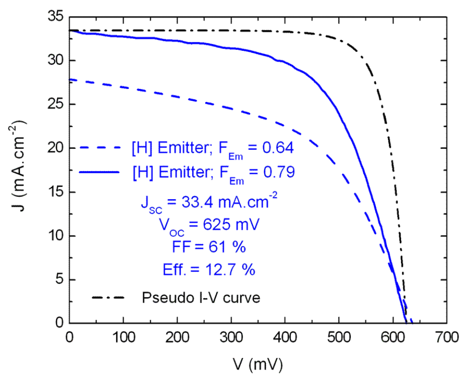

Figure 7. AM1.5 J-V curves of IBC Si-HJ cells - Influence of p-type a-Si:H emitter contact fraction - The pseudo I-V curve measured by SunsV_{oc} is shown for an F_{Em} of 0.79

With this higher emitter contact fraction, efficiency about 12.7% is obtained on 25 cm^2 cell area. This is to our knowledge the best results obtained for n-type IBC Si-HJ cells. The FF value slightly improves but the most impacted parameter is the J_{sc} reaching 33.4 $mA.cm^{-2}$. This confirms that the emitter contacting scheme has a great impact on the IBC Si-HJ cells efficiency as highlighted by our modeling results. However, the FF value is still low due to resistive losses in the metallization and the non-contacted emitter. To further enhance the cells efficiency the rear side geometry has to be improved by fully contacting the p-type a-Si:H emitter layer.

4 CONCLUSION

This work has shown the great influence of the emitter design for IBC Si-HJ solar cells optimization. A low emitter conductivity and / or low emitter contact fraction can induce a "shunted-like" behavior of the AM1.5 J-V curves as well a J_{sc} losses. These losses limit dramatically IBC Si-HJ cells efficiency. Thanks to rear geometry improvements an IBC-Si-HJ cell efficiency of 12.7% is achieved on 25 cm^2 n-type substrate. This is to our knowledge the best value reported on n-type c-Si.

5 ACKNOWLEDGEMENTS

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