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B-doped a-Si:H contact improvement on silicon heterojunction solar cells and interdigitated back contact structure

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This study reports on the p-type a-Si:H emitter layer of silicon heterojunction (Si-HJ) solar cells and its contacting scheme. The influence of the ratio between p-type a-Si:H emitter width and its contact width is checked on Interdigitated Back Contact (IBC) Si-HJ both experimentally and by 2D modelling. A low emitter contact fraction value is found to be detrimental to the IBC Si-HJ cells efficiency due to distributed series resistance effects. This not only limits the cell fill factor (FF) but also its short circuit current density (Jsc). By increasing the emitter contact fraction an efficiency of 12.7% is obtained on 25 cm^2 IBC Si-HJ solar cells. New B-doped a-Si:H emitter layers and contacts are also developed on inverted Si-HJ cells. Depending on the a-Si:H conductivity, we observe a great impact of the contact material on Si-HJ cells performance.

1 Introduction

The silicon heterojunction (Si-HJ) technology uses thin hydrogenated amorphous silicon (a-Si:H) layers deposited on crystalline silicon substrates. Applying this technology for solar cell fabrication shows several advantages such as low processing temperatures (below 300°C) and excellent surface passivation (high V_{OC}'s). The most efficient Si-HJ cells use the so called HIT^{TM} structure with an undoped (intrinsic) buffer layer between the c-Si substrate and the doped a-Si:H layers [1]. However the optimization of such buffer layer can be difficult because of possible band misalignment and /or insufficient conductivity especially for p-type layers [2][3]. Resistive losses induced by a buffer layer have also been observed for Interdigitated Back Contact (IBC) Si-HJ solar cells which show fill factor values below 60 % [4][5]. This limits the cells performance although modelling studies show that such structure is able to reach more than 24 % efficiency [6][7][8]. Without using a rear buffer layer higher FF values above 70 % have been obtained on IBC Si-HJ structures [6][8]. Our group have developed IBC Si-HJ cells without buffer layer and found that other parameters like a high contact resistance can also limit the cells efficiency value [9]. This study focuses on the different ways to enhance IBC Si-HJ efficiency by working on the p-type a-Si:H emitter layer and its contact. First we fabricate 25 cm^2 IBC Si-HJ (Fig.1) cells with a simple patterning process using thin metallic masks.

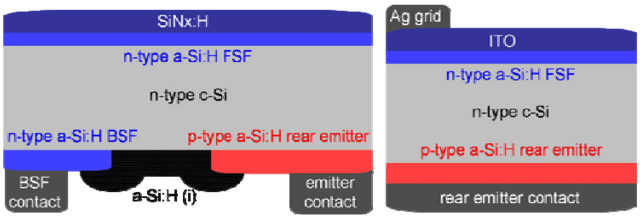

Figure 1 Sketches of the IBC Si-HJ (Left) and of the inverted Si-HJ (Right) cell.

The influence of emitter contact fraction on IBC Si-HJ cells is checked both experimentally and by means of 2D modelling. Then we try to optimize the p-type a-Si:H emitter layer and its contact material in order to enhance the surface passivation properties while limiting resistive losses. To achieve this we fabricate Si-HJ cells having the emitter layer deposited on the whole rear side, or so-called "inverted" Si-HJ cells [10], which fabrication process is easier than IBC cells (Fig.1). Inspired by previous modelling studies [11], we test experimentally the impact of rear emitter contact workfunction on inverted Si-HJ solar cells efficiency.

2 Experimental In this work 300 µm thick n-type FZ (100) oriented silicon wafers with a high bulk quality are used. They are polished with a 100 mm diameter and 1-5 Ω.cm resistivity. The native oxide removal is achieved by a 30 s dip in buffered HF without further rinse. Layers of a-Si:H are deposited in a Plasma Enhanced Chemical Vapor Deposition (PECVD) 13.56 MHz RF reactor at 200°C. As precursor gases we use SiH_4, H_2, PH_3 and TMB (TriMethylBoron) to obtain p-type, n-type and intrinsic (i) a-Si:H layers. Three different rear emitter contacts are used: Al and Ti with a low workfunction value ($\varphi \approx 4.3$ eV [12]) and Pd ($\varphi \approx 5.1$ eV [12]). These thin (0.1 µm) contact layers were covered by 1 µm thick Al to enhance the contact conductivity. All metal and Indium Tin Oxide (ITO) layers were sputtered in a magnetron chamber at a temperature below 200°C to avoid a-Si:H layers degradation. To fabricate the IBC we use patterned metallic stencils as shadow masks. A different mask is used for each a-Si:H, ITO and Al layer deposition with a mechanical alignment system.

The IBC Si-HJ cell structure comprises a 8 nm n-type a-Si:H / 80 nm SiN_x:H stack as front side anti-reflective coating achieving 25 cm s^{-1} effective recombination velocity and 85 % effective transmittance. The rear side geometry consists in interdigitated comb-shaped 27 nm thick p-type a-Si:H emitter and n-type a-Si:H Back Surface field (BSF) zones separated by a 40 nm thick insulating layer made of intrinsic (undoped) a-Si:H. 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. A short (5 min) anneal of the solar cells is necessary after ITO and Al deposition to obtain good ohmic contacts on doped a-Si:H layers. The "inverted" Si-HJ cells use the same thick a-Si:H emitter and BSF layers than IBC ones although the BSF is placed at the front side and therefore called Front Surface Field (FSF). A front Ag grid is screen-printed on the ITO layer whereas an emitter contact is sputtered on the full rear surface. LASER scribing is used at the end of the process to separate 25 cm^2 cells from the wafers. J–V characteristics under AM1.5 illumination (1000 $W \cdot m^{-2}$) were obtained on an "AESCUSOFT" solar simulator.

3 Results and discussion

3.1 Study of the emitter contact fraction of IBC Si-HJ cells With an IBC structure it is difficult to achieve a complete emitter covering due to possible short-circuits between emitter and base contacts. The IBC Si-HJ cell geometry implies indeed the alignment of different layers so that experimentally a fraction of the emitter and BSF layers can be left non-contacted. That is the reason why in our simple cell geometry (Fig. 1) only a fraction of the p-type a-Si:H emitter and n-type a-Si:H BSF is contacted. We fabricate IBC Si-HJ cells with different emitter contact fraction of 0.64 and of 0.79 to check the influence of this parameter. Figure 2 shows both AM1.5 illuminated Current–Voltage (I-V) curves and electrical parameters of the fabricated IBC Si-HJ devices. High V_{oc} values above 625 mV are obtained although no thin a-Si:H buffer layer is inserted under the doped a-Si:H layers. Our process is therefore adapted to pattern the different a-Si:H layers.

A low emitter contact fraction causes poor FF and Short Circuit Current (J_{sc}) values which limit the IBC Si-HJ cell efficiency below 10%. Increasing this parameter from 0.64 to 0.79 slightly enhances the cell FF to a value above 60 %. Surprisingly the most impacted parameter is the J_{sc} reaching 33.4 mA.cm^{-2}, i.e. 20 % relative increase of its value. This allows a cell efficiency of 12.7 % which is to our knowledge the best result for n-type IBC Si-HJ cells.

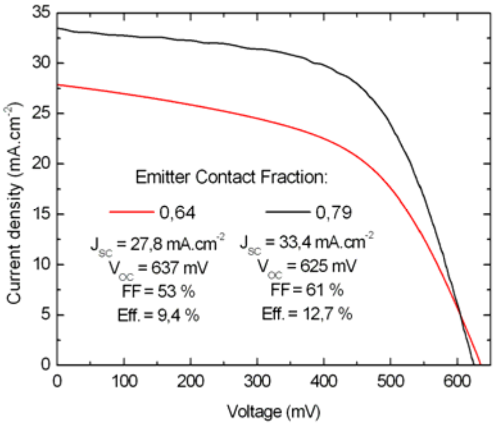

Figure 2 AM1.5 illuminated I-V curves and electrical parameters of 25 cm^2 IBC Si-HJ solar cells with different emitter contact fraction.

Both I-V curves show an untypical behaviour which limits the cells FF value. A first untypical decrease of the current value can be observed on the slope at low biases. A second decrease appears at biases near V_{oc}. This last behaviour can be attributed to standard series resistance (R_S) caused by the metallizations. Indeed the low Al thickness implies a R_S value of 2.4 Ohms.cm^2 in the cell which partially explains the low FF obtained. Thicker metallizations made by electroplating or screen printing can be used to decrease this R_S. The other untypical behaviour of the illuminated I-V is a current decrease already near J_{sc}. According to the double diode model this can be attributed to low (R_{SH}) values. However we measure high R_{SH} values above $1x10^4$ Ohm.cm^2 by the SunsV_{oc} implied I-V curves. This indicates that the device only suffers from resistive losses and no R_{SH} problems. Such behaviour of the illuminated I-V curve has already been observed on standard homojunction cells [13], however these untypical resistive losses have never been observed previously for Si-HJ cells. Indeed standard Si-HJ solar cells use an ITO layer which covers completely the a-Si:H emitter in order to enhance its very low lateral conductivity. This is not presently the case for our IBC structure on which only a fraction of the rear emitter is covered by a metal contact. Based on our previous modelling studies [7], the ATLAS software from Silvaco International was used to determine the influence of contacting scheme on the I-V curves of IBC Si-HJ cells. The rear side of the modelled structures consists in a 700 µm wide p-type a-Si:H emitter and 375 µm wide n-type a-Si:H BSF separated by 200 µm intrinsic a-Si:H. Both base and emitter electrodes are modelled by an ohmic contact covering a fraction of the doped a-Si:H layers. This model was used to determine the influence of the emitter contact fraction on the illuminated I-V curve of IBC Si-HJ cells. As shown in Fig. 3 this parameter has a great impact on the cells electrical parameters.

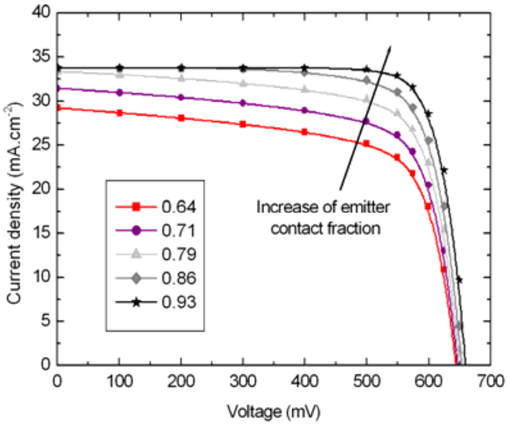

Figure 3 Simulated AM1.5 illuminated and SunsV$_{oc}$ implied I-V curves of a IBC Si-HJ solar cell with variable emitter contact fraction.

We use no additional series resistance in the simulated cells. Their J-V curves show therefore a better fill factor value than the experimental devices. However the simulation results confirm that a low emitter contact fraction value is detrimental not only for the cell FF but also for its J$_{SC}$ and therefore for the cell efficiency. These results show that further improvements in IBC Si-HJ cells geometry have to focus on fully contacting the B-doped a-Si:H emitter layer. To reach higher efficiencies an increase in J$_{sc}$ and V$_{oc}$ value is also necessary. On high quality c-Si wafers as it is the case for our cells, the V$_{oc}$ value mainly depends on surface passivation level. The second part of this study focuses on the optimization of B-doped a-Si:H emitters to enhance their passivation properties while not increasing resistive losses.

3.2 Optimization of B-doped a-Si:H emitter and contact on inverted Si-HJ cells

For n-type Si-HJ solar cells using no intrinsic layer, the emitter optimization mainly depends on the p-type a-Si:H layer conductivity and quality. We characterize the p-type a-Si:H layer quality by emitter saturation current density (J$_{0e}$) measurements [14]. We deposit 27+/-2 nm p-type a-Si:H on both sides of a n-type monocrystalline silicon wafer showing high bulk lifetime values. We vary the material doping by increasing the doping gas level into the deposition chamber from 10 sccm to 30 sccm and measure the p-type a-Si:H conductivity on glass. Two different p-doped a-Si:H materials with a low [L] and a higher [H] conductivity values (1.4x10^{-6} Ω^{-1}.cm^{-1} and 1.8x10^{-5} Ω^{-1}.cm^{-1}) are obtained. As shown in Fig. 4, the measured J$_{0e}$ depends both on the a-Si:H conductivity (and therefore doping level) and thickness.

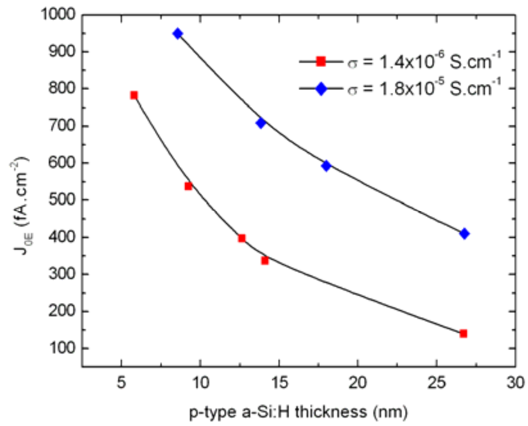

Figure 4 Influence of p-type a-Si:H layer conductivity on emitter saturation current density.

This shows that a lowly p-doped a-Si:H can reach quite low J$_{0e}$ values comparing to more doped a-Si:H layers. A higher doping means higher recombination rates and thus lower V$_{oc}$'s. The p-type a-Si:H material used for the previously fabricated IBC Si-HJ cells show a conductivity value of 1.8x10^{-5} S.cm^{-1}. This emitter layer induced a high J$_{0e}$ above 400 fA.cm^{-2} which limits the cell's V$_{oc}$ value. The use of a thick p-type a-Si:H layer is preferable to reduce J$_{0e}$ and enhance Si-HJ cells V$_{oc}$'s. This can be due to structural relaxation in the deposited a-Si:H with increasing layer thickness [15]. We therefore used the thick layers to fabricate 25 cm^2 inverted Si-HJ cells with different emitter conductivity and metal contact. According to [11] a metal workfunction above 5.3 eV is necessary to achieve flat band conditions and avoid depletion in the p-type a-Si:H emitter layer. Three different metal contacts were tested,

Table 1 Electrical parameters of inverted Si-HJ cells under AM1.5 illumination (mean value of at least 2 cells for each condition) - Influence of p-type a-Si:H emitter contact and conductivity.

σ (S.cm^{-1})	Contact (φ in eV)	V$_{oc}$ (mV)	J$_{sc}$ (mA/cm^2)	FF (%)	η (%)
1.8e-5	Al (4.3)	630	24.9	77.9	12.2
1.8e-5	Pd (5.1)	626	24.8	78.4	12.2
1.4e-6	Al (4.3)	646	25.8	64.7	10.8
1.4e-6	Ti (4.3)	653	26.0	73.4	12.5
1.4e-6	Pd (5.1)	650	25.8	75.6	12.7

Al and Ti having a workfunction value about 4.3 eV and Pd having a higher one (5.1 eV) [12]. Table 1 gives the electrical parameters of the fabricated cells.

Low J_{sc} values are obtained for all inverted Si-HJ cells due to light absorption in the thick n-type a-Si:H front surface field layer. Accordingly to J_{0e} measurements, the use of [L] emitters allows about 20 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}. However the low emitter conductivity has a negative impact on the cells FF whatever the contact material is. This can be explained both by a higher vertical resistivity in the thick a-Si:H layer and also by increased contact resistivity. In our case a Schottky barrier is likely to appear at the metal / a-Si:H interface for a low metal contact workfunction [11]. The measured I-V curves (Fig. 5) of inverted cells having a [L] emitter contacted by an Al layer are indeed clearly s-shaped. A higher workfunction [Pd] improves the fill factors up to 75 % by decreasing this barrier.

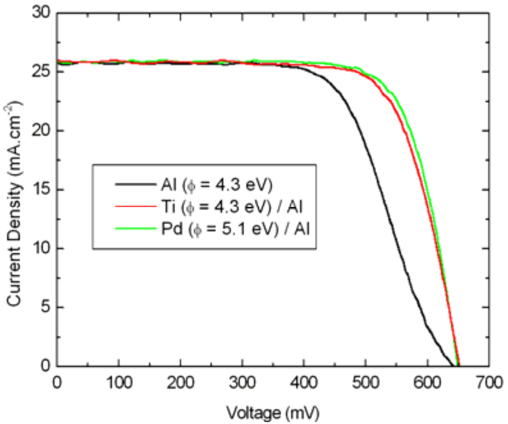

Figure 5 AM1.5 illuminated I-V curves of 25 cm^2 inverted Si-HJ solar cell with [L] emitter and different rear metal contact.

With [H] emitters the influence of the contact material is not as high as on lowly doped ones. Actually the measured cells fill factors values are above 77 % even with an [Al] contact which has a low workfunction. This confirms that an emitter stack of [H] p-type a-Si:H with an Al contact can be used on Si-HJ cells to obtain a high FF value. By using this emitter stack, no s-shape could indeed be seen on the J-V curves of the previously fabricated IBC devices. The higher a-Si:H doping makes probably tunnelling mechanisms dominate at the a-Si:H/metal interface so that the charge carriers are less influenced by the Schottky barrier [16]. The use of a high contact workfunction is here proven to reduce FF losses even when using lowly conductive p-type a-Si:H layers. However Ti contacts (low workfunction) does not induce s-shaped I-V curves. The metal contact workfunction cannot therefore be considered as the only parameter driving the contact resistivity on p-type a-Si:H emitters. For example the deposition of a metal layer over an a-Si:H layer can induce its partial or total recrystallization. This kind of material interaction at the metal / a-Si:H interface has now to be checked, for example by Transmission Electron Microscopy, for the different layers.

4 Conclusions

The rear emitter contacting scheme of IBC-Si-HJ cells has to be carefully designed to enhance their efficiency. The influence of the emitter contact fraction has been here demonstrated experimentally and by means of 2D modelling. An IBC-Si-HJ cell efficiency of 12·7% is obtained which is to our knowledge the best value reported on n-type sc-Si. Inverted Si-HJ cells have been fabricated to optimize the rear p-type a-Si:H emitter and its contact. High V_{oc}'s above 650 mV are obtained on these inverted cells having a less doped emitter layer comparing to 627 mV with the previously used ones. The contact workfunction is shown to have a great impact on the inverted Si-HJ cells fill factor, but other parameters such as material interaction at the metal / a-Si:H interface play a role as well. An Al layer induces poor contact quality even especially on lowly conductive emitter whereas the use of Pd greatly enhances FF values. Thanks to the contact optimization FF values up to 78.4% are shown for inverted cells. These results confirm that both p-type a-Si:H emitter conductivity and contacting scheme have a great impact on Si-HJ cells efficiency.

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References

[1] M. Tanaka et al., Jpn. J. Appl. Phys. **31,** 3518 (1992).
[2] F. Einsele, P.J. Rostan, M.B. Schubert, and U. Rau, J. Appl. Phys. **102,** 094507 (2007).
[3] U. Das, S. Bowden, M. Burrows, S. Hegedus, R. Birkmire, in: Conf. Rec. 4th IEEE WCPEC, Hawaii, USA, 2006, Vol. 2, pp. 1283–1286.
[4] M. Lu, S. Bowden, U. Das, and R. Birkmire, in: Proc. 22nd EPVSEC, Milano, Italy, 2007, pp. 924-927.
[5] M. Tucci et al., in: Proc. 23rd EPVSEC, Valencia, Spain, 2008, pp. 1749-1752.
[6] R. Stangl et al., in: Proc. 22nd EPVSEC, Milano, Italy, 2007, pp. 870-874.
[7] D. Diouf, J.P. Kleider, T. Desrues, and P.J. Ribeyron, Mater. Sci. Eng. B **159/160**, 291 (2009).
[8] U. Das et al, in: Proc. 18th Workshop on Crystalline Silicon Solar Cells & Modules 2008, pp. 70-77.
[9] T. Desrues et al., in: Proc. 23rd EPVSEC, Valencia, Spain, 2008, pp. 1673-1676.
[10] F. Wünsch, G. Citarella, O. Abdallah, and M. Kunst, J. Non-Cryst. Solids **352**, 1962 (2006).
[11] A. Froitzheim, R. Stangl, L. Elstner, M. Schmidt and W. Fuhs, in: Conf. Rec. 29th PVSC, New Orleans, USA, pp. 1238-1241.

[12] H. B. Michaelson, J. Appl. Phys. **48**(11), 4729 (1977).
[13] M. Wolf and H. Rauschenbach, Adv. Energy Conversion **3**, 455 (1963).
[14] D.E. Kane, R.M. Swanson, in: Conf. Rec. 18th IEEE PVSC, Las vegas, USA, 1985, pp. 578–583.
[15] S. Olibet, E. Vallat-Sauvain, and C. Ballif, Phys. Rev. B **76,** 35326 (2007).
[16] J. K. Arch, F. A. Rubinelli, J.-Y. Hou, and S. J. Fonash, J. Appl. Phys. **69**(10), 7058 (1991).