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# Demonstrating the high $V_{oc}$ potential of PEDOT:PSS/c-Si heterojunctions on solar cells

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## Abstract

In this study, we demonstrate the high surface passivation quality of PEDOT:PSS/c-Si junctions for the first time on solar cell level, reaching a record high $V_{oc}$ value of 688 mV after full-area metallization of the PEDOT:PSS. We achieve this by combining the PEDOT:PSS hole-selective layer at the rear of the crystalline silicon wafer with a well-passivating electron-selective a-Si:H(i/n) layer stack at the front. Our results clearly prove the excellent hole selectivity of PEDOT:PSS on crystalline silicon.

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*Keywords:* PEDOT:PSS; heterojunctions; solar cells; $V_{oc}$ potential

## 1. Introduction

In previous work, we demonstrated a very high $V_{oc}$ potential > 680 mV of PEDOT:PSS/c-Si junctions on lifetime samples, however, without any metallization [1]. We also demonstrated that PEDOT:PSS/c-Si junctions allow for high fill factors $FF > 80$ % and low series resistances $R_s < 0.6$ $\Omega\text{cm}^2$ on solar cell level [2]. However, the $V_{oc}$ of the solar cells fabricated in Ref. [2] was so far limited to a maximum achieved value of 663 mV, largely limited by the conventionally processed phosphorus-diffused front. A promising approach to exploit the full $V_{oc}$ potential of the

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PEDOT:PSS/c-Si junction (located at the cell rear) on solar cell level is the combination with an a-Si:H(i/n) silicon heterojunction at the front [3,4,5], which is known for its outstanding passivation quality [6].

## 2. Fabrication process

Figure 1 schematically shows the process flow of our PEDOT:PSS/c-Si/a-Si:H(i/n)/ITO solar cells. We use 180 µm thick boron-doped *p*-type Czochalski silicon (Cz-Si) wafers with a resistivity of 2.2 Ωcm. After an RCA cleaning, the wafers receive a protection layer at the cell rear. In a next step, the wafers are laser-cut into (8 × 8) cm² pseudo square pieces (YLP-C-2-1500-15-30, IPG Photonics) followed by a wet-chemical texture at the cell front and an RCA cleaning sequence. We then deposit a 24 nm thick a-Si:H(i/n) stack by means of plasma-enhanced chemical vapor deposition (PECVD) onto the full front side of the wafers. Then, the front side is coated with ITO sputtered through a shadow mask, resulting in four (2.2 × 2.2) cm² windows on the (8 × 8) cm² pseudo-square wafers (Octopus II cluster tool, INDEOtec). Finally, the front ITO is contacted by a screen-printed low-temperature silver paste cured for 20 minutes at 190°C (ASYS EKRA). Figure 2 shows a photograph of a fully processed wafer with 4 solar cells.

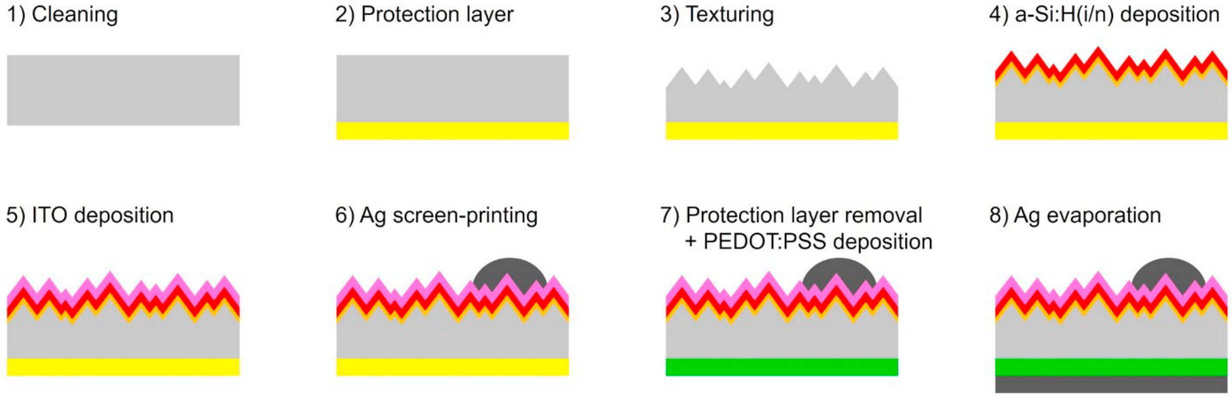

Fig. 1. Process flow of our PEDOT:PSS/c-Si/a-Si:H(i/n)/ITO solar cells.

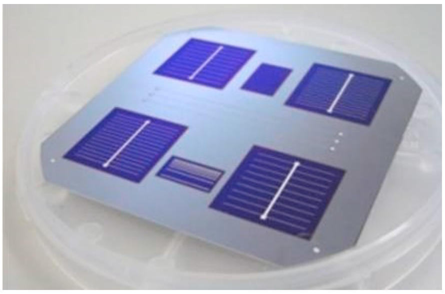

Fig. 2. Photograph of a (8 × 8) cm² pseudo square wafer with 4 solar cells. The ITO windows are (2.2 × 2.2) cm². The metal grid is designed for (2 × 2) cm² solar cells.

After finishing the front side of the solar cells, the protection layer on the rear side is removed by wet-chemical etching and the PEDOT:PSS layer is deposited by spin-coating onto the entire rear side of the (8 × 8) cm² pseudo square wafers at 500 revolutions per minute (rpm) for 10 seconds and subsequently 1000 rpm for 30 seconds (SUSS SM 240, KarlSuss). Then the samples are annealed on a hotplate in ambient air at 130°C for 10 minutes for drying and removing residual solvents. Finally, the entire rear surface is metallized with silver by means of e-gun evaporation (BAK 550, Balzer). The *I-V* characteristics and EL images are measured with and without a (2 × 2) cm² shadow mask using a LOANA tool (pv-tools).

## 3. Lifetime measurements

To estimate the $V_{oc}$ potential of our solar cells we measure the passivation quality of the different recombination contributions on lifetime samples. For the PEDOT:PSS/c-Si-junction samples we use 300 µm thick *p*-type float-zone (FZ) silicon wafers with a resistivity of ~150 Ωcm. After an RCA cleaning, we deposit a 100 nm thick $SiN_x$ surface-passivating layer by means of PECVD onto one side of the wafer. We then deposit the PEDOT:PSS dispersion using spin-coating and annealing at 130°C for 10 minutes in ambient air. We perform transient photoconductance decay (PCD) measurements and extract the saturation current densities in the range $J_0 = (50 - 80)$ fA/cm² on our lifetime samples using the Kane and Swanson method [7]. Note that the measured $J_0$ values also include the non-negligible recombination losses of the $SiN_x$-passivated surface of the samples. The reported $J_0$ values are hence upper limits to the true $J_0$ of the PEDOT:PSS/c-Si junction.

For the a-Si:H(i/n) layers we use the same 180 µm thick *p*-type Cz-Si wafers with a resistivity of 2.2 Ωcm as for our solar cells. For these samples we measure a total $J_0$ of 26 fA/cm², including the surface passivation as well as the bulk properties of our Cz-Si wafers.

Estimating the total $V_{oc}$ potential of our solar cell using the Shockley diode equation with an ideality factor of $n = 1$ leads to values of $V_{oc} = (682 - 691)$ mV. Note that these values are a lower limit due to the design of the lifetime test samples as explained above.

## 4. Solar cell results

Table 1 shows the performances of 3 PEDOT:PSS/c-Si/a-Si:H(i/n)/ITO heterojunction solar cells processed on the same wafer. Remarkable are the high $V_{oc}$ values of (675 – 680) mV, measured with a (2 × 2) cm² shadow mask. Measuring the cells without shadow mask even improves the $V_{oc}$ up to 688 mV, which reveals the actual $V_{oc}$ potential of the cells.

Table 1. Solar cell parameters of our PEDOT:PSS/c-Si heterojunction solar cells measured with a shadow mask. The $V_{oc}$ values in brackets belong to measurements without shadow mask.

| With mask | $V_{oc}$ [mV] | $J_{sc}$ [mA/cm²] | *FF* [%] | *pFF* [%] | $R_s$ [Ωcm²] | η [%] |
|---|---|---|---|---|---|---|
| Cell #1 | 680 (688) | 31.7 | 74.1 | 78.7 | 1.24 | 16.0 |
| Cell #2 | 679 (688) | 32.0 | 74.3 | 78.8 | 1.19 | 16.2 |
| Cell #3 | 675 (682) | 31.9 | 74.4 | 79.1 | 1.25 | 16.0 |

The reason for the reduced $V_{oc}$ on the cells measured with shadow mask is the dark diode at the periphery of the cell, which is electrically coupled to the illuminated cell area. Figure 3 shows EL images of the champion cell measured (A) without and (B) with shadow mask. The bright area in image A is the (2.2 × 2.2) cm² ITO window. In the case of a masked measurement, this leads to a coupling of the peripheral dark diode, which lowers the $V_{oc}$. Optimizing the ITO deposition area would therefore directly lead to increased $V_{oc}$ values also for masked measurements.

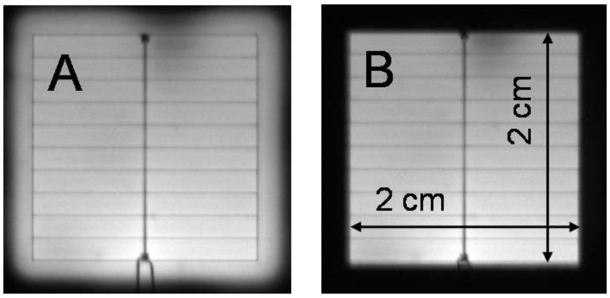

Fig. 3. EL images of one of our PEDOT:PSS/c-Si/a-Si:H(i/n)/ITO heterojunction solar cells measured (A) without and (B) with shadow mask.

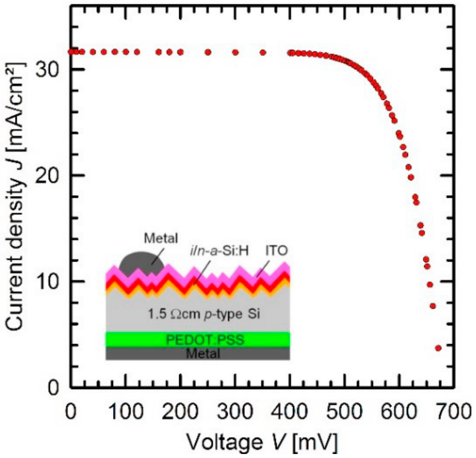

Fig. 4. *I-V* curve of our PEDOT:PSS/c-Si/a-Si:H(i/n)/ITO heterojunction solar cell #1. The inset shows a schematic drawing of the solar cell.

The $V_{oc}$ of the solar cells measured without shadow mask agree very well with the $V_{oc}$ potential determined using the lifetime test samples. This clearly proves for the first time that the excellent passivation of the Si surface by PEDOT:PSS can be fully preserved after the complete PEDOT:PSS surface has been metallized. Figure 4 shows the *I-V* curve of cell #1.

Note that the full potential of this cell type could not be exploited in this study due to relatively low $J_{sc}$ and *FF* values. The $J_{sc}$ is mainly limited by a strong parasitic absorption in the front a-Si:H(i/n)/ITO stack at the front and also in the PEDOT:PSS layer at the back. One possible explanation for the low *FF* is the fact that the *a*-Si:H(*i*/*n*) stack is optimized for *n*-type *c*-Si solar cells, where it acts as back surface field (BSF) and not, as in our case, as emitter on our *p*-type wafers. For this reason we have to adjust the thickness and doping of the *a*-Si:H(*i*/*n*) layer stack to further improve the solar cell performance. However, we already demonstrated high $J_{sc}$ values of 38.9 mA/cm² and *FF* values of 80.6 % ($R_s < 0.6\ \Omega\text{cm}^2$) with PEDOT:PSS/c-Si junctions on solar cells with a conventionally processed phosphorus-diffused front [2]. Hence, the PEDOT:PSS implemented to the rear surface of a silicon solar cell shows a clear potential for high efficiencies.

## 5. Summary

In this study we have combined a PEDOT:PSS hole-selective layer at the rear with a well-passivating electron-selective a-Si:H(i/n) layer stack at the front of our solar cells. We have reached a $V_{oc}$ value of 680 mV when measuring the cell with a shadow mask. However, we have shown that this value is reduced by a dark diode at the periphery of the cell, which is electrically coupled to the illuminated cell area. Therefore, measuring the cell without shadow mask reveals the actual record high $V_{oc}$ of 688 mV. Hence, we have demonstrated the high surface passivation quality of PEDOT:PSS/c-Si junctions for the first time on solar cell level, even after full area metallization.

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## References

[1] Schmidt J, Titova V, Zielke D. Organic-silicon heterojunction solar cells: Open-circuit voltage potential and stability. Appl. Phys. Lett. 2013;103:183901 1-4.

[2] Zielke D, Niehaves C, Lövenich W, Elschner A, Hörteis M, Schmidt J. Organic-inorganic solar cells exceeding 20% efficiency. Energy Procedia; 2015; 77; p. 331-339.

[3] Gogolin R, Zielke D, Lövenich W, Sauer R, Schmidt J. Silicon heterojunction solar cells combining an a-Si:H(n) electron-collector with a PEDOT:PSS hole-collector. Energy Procedia; 2016; 92; p. 638-643.

[4] Wen H, Cai H, Du Y, Dai X, Sun Y, Ni J, Li J, Zhang D, Zhang J. Improving the organic/Si heterojunction hybrid solar cell property by optimizing PEDOT:PSS film and with amorphous silicon as back surface field. Appl. Phys. A; 2017;123:14.

[5] Zhang X, Yang D, Yang Z, Guo X, Liu B, Ren X, Liu S. Improved PEDOT:PSS/c-Si hybrid solar cell using inverted structure and effective passivation. Scientific reports; 2016;6:35091 1-8.

[6] Yoshikawa K, Kawasaki H, Yoshida W, Irie T, Konishi K, Nakano K, Uto, T, Adachi D, Kanematsu M, Uzu H, Yamamoto K. Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%. Nature Energy; 2017;2:17032.

[7] Kane DE, Swanson RM. Measurement of the emitter saturation current by a contactless photoconductivity method. Proc. 18th IEEE Photovoltaic Spec. Conf. 1985; p. 578 -581.