Contents lists available at ScienceDirect

# Nano Energy



journal homepage: www.elsevier.com/locate/nanoen

## Full paper

# Realization of interdigitated back contact silicon solar cells by using dopantfree heterocontacts for both polarities



Hao Lin<sup>a,b</sup>, Dong Ding<sup>a</sup>, Zilei Wang<sup>b</sup>, Longfei Zhang<sup>b</sup>, Fei Wu<sup>a</sup>, Jing Yu<sup>b</sup>, Pingqi Gao<sup>b,\*</sup>, Jichun Ye<sup>b,\*</sup>, Wenzhong Shen<sup>a,\*</sup>

<sup>a</sup> Institute of Solar Energy, and Key Laboratory of Artificial Structures and Quantum Control (Ministry of Education), Department of Physics and Astronomy, Shanghai Jiao Tong University, 800 Dong Chuan Road, Shanghai 200240, PR China

<sup>b</sup> Ningbo Institute of Material Technology and Engineering, Chinese Academy of Sciences (CAS), Ningbo 315201, PR China

#### ARTICLE INFO

Keywords: Heterojunction solar cell PEDOT:PSS hybrid solar cells Interdigitated back contact Dopant-free Carrier-selective contacts

#### ABSTRACT

For crystalline-silicon (c-Si) solar cells, the interdigitated back contact (IBC) structure has been long known as an efficient way to approach the theoretical limit of efficiency. However, the complexity of fabricating this kind of devices as well as the high dependence on expensive vacuum systems pose concerns about their commercial potential. Here, we demonstrate a novel c-Si IBC solar cell featuring dopant-free heterocontacts for both polarities, i.e. a solution-proceeded PEDOT:PSS film as hole-transporting layer (HTL) and an evaporated magnesium-oxide film as electron-transporting layer (ETL). Our innovatively buried ETL method provides substantial simplification on the architecture and fabrication of the IBC cells and makes it possible to adapt solution-proceeded HTLs while keeping good passivation in gap regions. The IBC solar cell shows an efficiency of 16.3%, with a promising short-circuit current density ( $J_{sc}$ ) up to 38.4 mA/cm<sup>2</sup>. A thorough simulation concerning the influence of pitch size, surface recombination rate (at ETL and gap regions) was conducted, revealing a readily achievable  $J_{sc}$  of 41 mA/cm<sup>2</sup> and a PCE beyond 22%. Our findings demonstrated a feasibility of using solution method to fabricate high efficiency dopant-free IBC solar cells.

#### 1. Introduction

Routine improvements have led to exceptional success of crystalline silicon (c-Si) solar cells, demonstrated by a new record power conversion efficiency (PCE) of 26.7% from an interdigitated back contact (IBC) solar cell combining with advanced heterojunctions (HJs) [1]. The IBC structure has been long known as an efficient way to avoid shading losses and enable full-area passivation on front side because all electrodes are placed on the non-illuminated rear side. Meanwhile, the HJs comprising bilayer films of intrinsic amorphous silicon (a-Si:H) and doped a-Si:H play another important role of passivating contact or carrier-selective contact (CSC). The two-fold designs of IBC-HJs are responsible for the highest efficiency by now and could be the possible roadmap towards 29.4%, a theoretical efficiency limit for single junction c-Si solar cells. However, such solar cells suffer from complex processing in patterning discrete contacts to the rear side as well as extremely high facilities investment (more than 4 times to the current mainstream technique). This severely hinders the industrialization for high volume production. In addition, parasitic electrical and optical losses inherent to the doped layers restrain further promotion on efficiency. Thus, a few activities have been moved to seeking simplified solutions, such as implementation of high-performance IBC-HJs solar cells via dopant-free manner.

Functional thin films with high/low work function (WF) have thus been paid much interest in c-Si solar cells for the formation of dopantfree hole/electron-selective contacts. Most of the functional materials can be deposited via low-temperature and/or solution-based processing, such as spin-coating or thermal evaporation, providing big potentials in both doping elimination and procedure simplification (especially for IBC-HJs) [2,3]. So far, poly(3,4-ethylenedioxythiophene):polystyrene (PEDOT:PSS) [4,5] and transition metal oxides (TMOs), such as molybdenum oxide (MoOx) [6,7], tungsten oxide  $(WO_x)$  [8] and vanadium oxide  $(V_2O_x)$  [9], all with high WFs have been successfully demonstrated as hole-transporting layers (HTLs). Meanwhile, low WF materials including titanium oxide  $(TiO_x)$  [10,11], magnesium oxide (MgO<sub>x</sub>) [12,13], lithium fluoride (LiF<sub>x</sub>) [14], etc. have always been served as electron-transporting layers (ETLs). Due to ease of processing, tailorable optoelectronic properties, facile integration of conducting polymers [15], PEDOT:PSS/Si heterojunction solar cells, especially for the structure of FrontPEDOT:PSS, have been

\* Corresponding authors. E-mail addresses: gaopingqi@nimte.ac.cn (P. Gao), jichun.ye@nimte.ac.cn (J. Ye), wzshen@sjtu.edu.cn (W. Shen).

https://doi.org/10.1016/j.nanoen.2018.06.013 Received 21 April 2018; Received in revised form 28 May 2018; Accepted 5 June 2018 Available online 15 June 2018 2211-2855/ © 2018 Published by Elsevier Ltd.



emerging with a fast promotion of PCEs from below 10% to beyond 16% [16]. Regardless of this distinct advance, development of IBC-like PEDOT:PSS/Si solar cells is beneficial to circumvent the barriers that are relevant to the front-sided PEDOT:PSS layer, including parasitic absorption, poor anti-reflection and inferior coating quality upon the Sitextures [17–19]. However, proven feasibility of solution-processed PEDOT:PSS/Si IBC solar cells is pending. Knowledge regarding the rearsided partial HTLs with PEDOT:PSS and the matched ETLs, as well as the integration of those contact materials in the c-Si solar cell architectures, is still in its infancy. Therefore, experimental attempts can help us to understand this novel device in more details at the aspects including interfaces, contact ratios, processing related issues, etc., directly guiding the evaluations and designs of high-performance dopant-free IBC-HJs cells.

Here, aiming at the achievement of high efficiency IBC-type organic/Si heterojunction solar cells via a low-temperature processing and dopant-free manner, a new device structure with hole-selective contacts of PEDOT:PSS/Si and buried electron-selective contacts of MgO<sub>x</sub>/Si was developed. With optimizing the contact properties for both polarities and the pitch ratios between them, our IBC device achieved a PCE of 16.3%, with an open-circuit voltage ( $V_{oc}$ ) of 581 mV, a fill factor (*FF*) of 73.1% and a short-circuit current density ( $J_{sc}$ ) of 38.4 mA/cm<sup>2</sup>. This result fully demonstrated that high-performance IBC-HJs solar cells can be even made of spin-coated and evaporated materials, exempting the heavy dependence on high-temperature doping or expensive chemical vapor deposition processes. Furthermore, a prospective PCE exceeding 22% for the PEDOT:PSS/Si based IBC cell was predicted once the surface recombination rate at ETL/Si interface can be reduced below 100 cm/s.

#### 2. Results and discussion

As shown in Fig. 1a, the *n*-type c-Si wafer with front-sided pyramidstexture was selected as the substrate for construction of our IBC solar cells. On the front surface, Al<sub>2</sub>O<sub>3</sub> and SiN<sub>x</sub> films were deposited as passivation and an anti-reflection layer. The PEDOT:PSS/Ag and MgOx/ Al structures were interdigitated on the rear surface of the c-Si, serving as hole- and electron-selective contacts, respectively. We wrapped up the MgO<sub>x</sub>/Al contacts with a polymer layer before spin-coating the PEDOT:PSS film (Fig. 1b). Thus, the PEDOT:PSS/Ag contacts covered the whole rear surface of the device except for the busbar that was connected with the MgOx/Al electrode and must be kept open for testing. Fig. 1c shows a cross-sectional SEM image of one back-contact, while Fig. 1d-f exhibit the corresponding magnified images collected from the white-square regions marked in Fig. 1c (from left to right). From Fig. 1d, one can clearly see that the  $MgO_x$  layer together with the capped Al electrode have a total thickness of around  $1 \,\mu\text{m}$ . The MgO<sub>x</sub>/ Al portion was well wrapped by a polymer film. Meanwhile, this polymer layer does play another two important functions, i.e. isolating the HTL and ETL regions with gaps and protecting the underneath Al<sub>2</sub>O<sub>3</sub> layer (pre-deposited for surface protection) from etching during the area-opening (for deposition of HTLs). Fabrication process please refer to Fig. S1. The survived Al<sub>2</sub>O<sub>3</sub> layer thus provide sufficiently high quality of passivation to the gap regions, which is crucial to obtain high efficiency IBC solar cells. Fig. 1e and f show a good coverage, even at the boundary area between HTL and the polymer, of PEDOT:PSS film on the entirely bared c-Si surface. This is very important for achieving high quality of passivation at HTL regions. Due to the shield effect during the spinning coating process, the thickness of PEDOT:PSS film near the gap region is thicker than that on other areas, reaching at about 100 nm.

According to the location of the PEDOT:PSS film in a device, the hybrid solar cells can be categorized as three types: Front-PEDOT (Fig. 2a), Back-PEDOT (Fig. 2b) and IBC-PEDOT (Fig. 2c). For straightforwardly understand the optical and electrical losses of these three types devices, the *J*-V curves and the photovoltaic (PV)

performance are shown in Fig. 2e and Table 1, respectively. One can find that the Front-PEDOT and Back-PEDOT devices possessed relatively higher Voc of about 620 mV, compared to that of IBC-PEDOT (581 mV). We note that the lower  $V_{\rm oc}$  of the IBC-PEDOT is partially ascribed to high resistivity of Si wafer (1–10  $\Omega$  cm) we chosen. It was reported that the V<sub>oc</sub> of PEDOT:PSS/Si hybrid solar cells has a positive correlation with the doping concentration of Si substrates [20]. While the Si substrate with higher bulk resistance is better for construction of IBC device due to higher lifetime [21]. The other reason that responsible for the high  $V_{\rm oc}$  of both Front-PEDOT and Back-PEDOT solar cells is the utilization of a-Si:H(i)/a-Si:H(n) as ETL. Actually, our IBC device with ETL of MgO<sub>x</sub> can only provide a moderate level of passivation. Even so, the IBC device still received a high PCE of 16.3% due to the highest  $J_{sc}$  of 38.4 mA/cm<sup>2</sup>, in comparison with 31.8 and 34.9 mA/ cm<sup>2</sup> for the Front-PEDOT and Back-PEDOT devices, respectively. As shown in Fig. 2f, the Front-PEDOT device shows the lowest EQE value and the highest overall reflection. While the IBC-PEDOT device shows much better EQE almost over the whole useful wavelength range, indicating superior light harvesting and carrier collection efficiency. The  $J_{\rm sc}$  losses are calculated according to the experimental results (more details are shown in Fig. S2) and correspondingly presented in Fig. 2d1-3. The optical losses caused by electrode shade, reflection and parasitic absorption are clearly noted. Besides, the recombination caused losses are assessed by subtracting the optical losses from the gross  $J_{sc}$  losses (assuming the best  $J_{sc}$  value of 44 mA/cm<sup>2</sup>) [22]. So, the recombinative losses for Back-PEDOT, Front-PEDOT and IBC-PEDOT device are estimated as 1.5, 1.9 and  $5.5 \,\text{mA/cm}^2$ , respectively.

It is well known that a good ETL should has not only good passivation, but also low contact resistivity ( $\rho_c$ ). The MgO<sub>x</sub> layer is applied as ETL here mainly due to its convenience for processing, good stability and moderate passivation [12]. To investigate the ETL of MgO<sub>x</sub> layer used here, a series of planar Front-PEDOT solar cells with varied thickness of MgO<sub>x</sub> films were fabricated. The schematic diagram of this kind of device is shown in Fig. 3a. Two corresponding TEM images collected from the black-square regions at the front and the back interfaces are exhibited in Fig. 3b and c, respectively. From Fig. 3b, we can obviously see a thin silicon oxide (SiO<sub>x</sub>) layer existing between the c-Si and PEDOT:PSS. The presence of SiOx layer has been proven as a key factor for better passivation at the PEDOT:PSS/Si interface [23]. While for the vacuum proceeded MgO<sub>x</sub>, no distinguishable silicon oxide layer exists at the interface of MgOx/Si (Fig. 3c). Nevertheless, a moderate level of passivation was provided by the MgO<sub>x</sub> film on the Si surface, supporting by the minority carrier lifetime mapping on the symmetric structure of MgO<sub>x</sub>/n-Si/MgO<sub>x</sub> (Fig. S3). The average minority carrier lifetime of the sample is about 20 µs, which corresponds a calculated surface recombination velocity of 621 cm/s. The  $V_{\rm oc}$  and  $J_{\rm sc}$ as a function of the thickness of MgO<sub>x</sub> films are shown in Fig. 3d, while the relevant evolutions of FF and  $\rho_c$  are shown in Fig. 3e. One can see that the  $V_{\rm oc}$  ( $J_{\rm sc}$ ) increases quickly from 559 (25.8) to 591 mV (27.3 mA/cm<sup>2</sup>) for the thickness of  $\rm MgO_x$  ranging from 0 to 0.6 nm, and then keeps near a constant with the thickness up to 1.8 nm. This result indicates that a moderate passivation of MgO<sub>x</sub> layer can be quickly obtained when the thickness is large than 0.6 nm. With further increasing the thickness of  $\mbox{MgO}_x$  film, the contact resistivity was dramatically increased from 15 m $\Omega$ ·cm<sup>2</sup> at 0.6 nm to ~ 1500 m $\Omega$  cm<sup>2</sup> at 3 nm, leading to severe deterioration in the FF. A full trend of J-V curves along with the MgO<sub>x</sub> thickness is shown in Fig. S4. One can see that a very thin MgOx layer, i.e. 0.2, 0.6 or 1.2 nm can help to get Ohmic contact properties, possibly owing to the Fermi level depinning effect. While the further increase of the thickness will cause a large resistive barrier for electron tunneling. Therefore, considering the balance between the passivation quality and the resistive losses, a thickness of  $MgO_x$  film among 0.6–1.2 nm will give the best PCE (see Table S2). Thus, 1 nm-thick MgO<sub>x</sub> film is selected for constructing IBC devices.

Planar IBC solar cells with HTL of PEDOT:PSS and ETL of  $MgO_x$  were then fabricated, as schematically shown in Fig. 4a. In order to



Fig. 1. The structure of PEDOT:PSS/Si based IBC-HJs solar cell. (a) Schematic of the IBC-HJs device. (b) The cross-sectional view of the back-contact region. (c) Corresponding SEM images of the back-contact region. (d–f) Magnified SEM images of the white-square region in (c) from left to right, respectively. Scale bars,  $10 \,\mu m$  in (c) and 200 nm in (d–f).

study the effect of pitch sizes on the PCEs, the ratio of HTL:ETL:gap was fixed at 48%:32%:20% [24]. The PV performance of our planar IBC-PEDOT cells is listed in Table 2. With decreasing pitch from 1000 to 100  $\mu$ m, the  $J_{sc}$  raises from 28.8 to 35.0 mA/cm<sup>2</sup>, the  $V_{oc}$  decreases slightly by about 15 mV, while the *FF* almost keeps at a stable value of 71%. As a result, the PCE of the device increases from 11.8% to 14.4%.

In order to well understand above-mentioned phenomena, carrier transport properties of IBC device should be investigated. As shown in Fig. 4a, since the HTL interdigitated with ETL on the rear side, photogenerated minority carriers (holes in n-type Si) above HTL have a large probability be transported to HTL and directly contribute to the  $J_{sc}$ . While holes above the noncollecting region (including ETL and gap portions) have a large probability to be annihilated firstly if the ETLs with poor passivation were used [25,26]. Meanwhile, broad width of noncollecting region will extend the average lateral distance for holes transport and increase the probability of recombination [21]. Therefore, increasing the width of ETL region (the width of ETL increase from 32 µm to 320 µm along with the increase of pitch in Table 2) will decrease the final collection probability of holes to HTL and lead to a low  $J_{sc}$ . The relations between PV parameters and the pitch sizes under three different passivation levels, i.e. poor ( $S_{ETL} = 10^6$  cm/s), moderate

( $S_{\rm ETL}$  = 1000 cm/s) and good ( $S_{\rm ETL}$  = 10 cm/s), were simulated and showed in Fig. 4b-d, respectively, where  $S_{\text{ETL}}$  is the surface recombination rate at ETL. From the results, we can clearly see that the PCEs of the devices with poor ETL passivation are always limited by the extremely low  $J_{sc}$ , showing a value below 11% for all the pitches. While for the good ETL passivation, all the PV parameters can be maintained at a quite high level, with  $V_{oc}$ ,  $J_{sc}$ , and PCE of 650 mV, 38 mA/cm<sup>2</sup> and 20%, respectively. In term of the moderate passivation case with  $S_{\rm ETL}$  of  $10^3$  cm/s, the V<sub>oc</sub>, J<sub>sc</sub> and PCE have a significant dependence on the pitches. The  $J_{\rm sc}$  declines with the pitch size very quickly while the  $V_{\rm oc}$ increases slowly, and the best PCE occurs at the smallest pitch. The simulated evolution trends for the moderate passivation case are well consistent with those of the experimental results of IBC-PEDOT devices with 1 nm MgO<sub>x</sub> film. This is reasonable because the  $S_{\rm eff}$  for our 10 nm MgO<sub>x</sub> on c-Si is around 621 cm/s. We should note here that the simulated PCEs are slightly higher than those collected from experiments because the overestimated FF of 80% in simulation.

In IBC-PEDOT cells, the photogenerated carriers that are mainly located at the front surface must be transported to the rear side and then be collected by the HTL and ETL electrodes. This is well different to the conventional double-sided junction solar cells, in which a



Fig. 2. Comparison of the three kinds of PEDOT:PSS/Si heterojunction devices. Schematics of (a) Front-PEDOT, (b) Back-PEDOT and (c) IBC-PEDOT devices. (d1–d3) Corresponding  $J_{sc}$  losses estimated by experimental results. (e) Light *J-V* curves and (f) Reflection and EQE spectra for the three kinds of devices.

Table 1				
Photovoltaic characteristics	of the three kinds	of PEDOT:PSS/Si	heterojunction sola	ar cells

Samples <sup>a</sup>	$V_{\rm oc}^{\ b}$ (V)	$J_{\rm sc}^{\rm b}$ (mA/cm <sup>2</sup> )	FF <sup>b</sup> (%)	PCE <sup>b</sup> (%)
Front-PEDOT Back-PEDOT IBC-PEDOT	$\begin{array}{l} \textbf{0.622} \ (0.619 \ \pm \ 0.007) \\ \textbf{0.617} \ (0.615 \ \pm \ 0.006) \\ \textbf{0.581} \ (0.576 \ \pm \ 0.007) \end{array}$	<b>31.8</b> (31.9 ± 0.4) <b>34.9</b> (34.7 ± 0.3) <b>38.4</b> (38.4 ± 0.3)	<b>71.8</b> (70.2 ± 1.7) <b>72.6</b> (71.4 ± 1.2) <b>73.1</b> (71.3 ± 1.4)	$\begin{array}{l} \textbf{14.2} (13.9 \ \pm \ 0.2) \\ \textbf{15.6} (15.2 \ \pm \ 0.4) \\ \textbf{16.3} (15.8 \ \pm \ 0.4) \end{array}$

<sup>a</sup> Data and statistics based on five cells of each condition.

<sup>b</sup> Numbers in bold are the champion values of each condition.

relatively poor rear-sided passivation may not cause significant influence on the  $J_{\rm sc}$ . In IBC-PEDOT, however, lack of or insufficient passivation is likely to lead to the decrease of  $V_{oc}$  as well as  $J_{sc}$ . Poor passivation in gap regions would result in recombination of carriers before they are collected at the junction [27]. The difference in carrier transport channels for the passivation-free and the Al2O3-passivated gaps are schematically shown in Fig. 5a. In order to quantitatively analyze the influence of gap passivation on the PV performance, corresponding simulation with varied  $S_{\rm gap}$  and  $S_{\rm ETL}$  are exhibited in Fig. 5b, c and d, respectively. As shown in Fig. 5b-d, the importance of gap passivation on the PV performance is fully displayed, especially when  $S_{\rm ETL} < 10^3$  cm/s. In other words, when the ETL regions are passivated beyond moderate level, the gap passivation plays a decisive role in the performance of our IBC-PEDOT device. For example, as  $S_{\text{ETL}}$ = 10 cm/s but  $S_{gap} = 10^4$  cm/s, the  $J_{sc}$ ,  $V_{oc}$  and PCE will still be quite poor as 29.4 mA/cm<sup>2</sup>, 548 mV and 12.6%, respectively. In addition, we can draw another conclusion that the  $J_{sc}$ ,  $V_{oc}$  and PCE all can be kept at a nearly high constant value when  $S_{\rm ETL} < 10^2$  cm/s for each determined  $S_{gap}$ , and then decreases quickly when the  $S_{ETL}$  increasing

from  $10^2$  cm/s to  $10^5$  cm/s. Except for the planar IBC-PEDOT device, the IBC-PEDOT device with pyramids-texture on the front side was also simulated and shown in Fig. 5b–d. With the same  $S_{gap}$  of 5 cm/s, applying the pyramids-texture on the front surface will predict a  $J_{sc}$  up to 41.6 mA/cm<sup>2</sup> and PCE exceeding 22.4%. At last, our best experimental results at this stage are marked as yellow stars in Fig. 4b–c, pointing out a relatively large space for promotion of the PCE. Future research will be emphasized on how to reduce the  $S_{ETL}$  and improve the *FF*.

### 3. Conclusions

In summary, we have fabricated a PEDOT:PSS/Si heterojunction allback-contacted (IBC-PEDOT) solar cell with efficiency over 16.3%. We successfully demonstrated a reasonable design of buried ETL method that not only substantially simplifies the architecture and fabrication of back-contacted silicon solar cells, but also makes it possible to adapt solution-proceeded HTL and keeps a good passivation in the gap region. Although the optimized ETL of 1 nm-thick MgO<sub>x</sub> film in this work can delivery moderate level of passivation and acceptable contact



**Fig. 3.** Optimization of MgO<sub>x</sub> film. (a) Schematic of a planar Front-PEDOT device with rear-sided MgO<sub>x</sub> film. TEM images for (b) PEDOT:PSS/Si interface and (c) Si/MgO<sub>x</sub>/Al interface. (d) The  $V_{oc}$  and  $J_{sc}$  as a function of MgO<sub>x</sub> thickness. (e) The *FF* and  $\rho_c$  as a function of MgO<sub>x</sub> thickness. The scale bars in (b) and (c) are both 5 nm.



Fig. 4. Influence of intercontact pitch and ETL passivation to photovoltaic properties of IBC-PEDOT solar cells. (a) Schematic structure of the simulated planar IBC-PEDOT device. (b–d) Simulated data of  $J_{sc}$  (b),  $V_{oc}$  (c), PCE (d) as functions of pitches and  $S_{ETL}$ .  $S_{gap} = 5$  cm/s.

 Table 2

 Photovoltaic performance of planar IBC solar cells with different pitches.

Pitch <sup>a</sup> (µm)	$V_{\rm oc}$ (V)	$J_{\rm sc}~({\rm mA/cm^2})$	FF (%)	PCE (%)
100 200 500 1000	$\begin{array}{rrrr} 0.572 \ \pm \ 0.015 \\ 0.561 \ \pm \ 0.011 \\ 0.581 \ \pm \ 0.013 \\ 0.589 \ \pm \ 0.006 \end{array}$	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	$71.7 \pm 2.0 71.1 \pm 1.0 71.7 \pm 0.7 69.4 \pm 3.2$	$\begin{array}{rrrr} 14.4 \ \pm \ 0.3 \\ 13.2 \ \pm \ 0.5 \\ 12.7 \ \pm \ 0.9 \\ 11.8 \ \pm \ 0.7 \end{array}$

<sup>a</sup> Data and statistics based on five cells of each condition.

resistance, it is still insufficient. At last, a thorough simulation of the influence of pitch,  $S_{\text{ETL}}$  and  $S_{\text{gap}}$  on the PV performance revealed that the PEDOT:PSS/Si heterojunction IBC solar cell with pyramids-texture can be readily pushed to a high level with  $J_{\text{sc}}$  exceeding 41 mA/cm<sup>2</sup> and PCE beyond 22% once the surface recombination rate of ETL can be controlled below 100 cm/s.

#### 4. Experimental section

### 4.1. IBC-PEDOT solar cells fabrication

Double-side polished, Czochralski, *n*-type  $(1-10 \Omega \text{ cm})$  wafers with a thickness of 250 µm were directly used to fabricate planar IBC-PEDOT solar cells. Randomly pyramids-textured wafers were prepared through immersing one-side of Si wafer into 80 °C mixed solutions with 2.5% KOH and 1.25% isopropanol for 15 min, while protecting the other side by a homemade tool. The processing flow for fabricating IBC-PEDOT cells can refer to Fig. S1. Firstly, after cleaning the wafers by a standard RCA1/2 [28] and removing native silicon oxide by a 4% HF solution, a

15 nm Al<sub>2</sub>O<sub>3</sub> thin film was deposited as passivation layer by atomic layer deposition (ALD) system, and then an 85 nm-thick SiNx film for pyramid-texture device and a 70 nm-thick Al<sub>2</sub>O<sub>3</sub> film for planar device was deposited as anti-reflection layer by plasma-enhanced chemical vapor deposition (PECVD) and E-beam evaporation, respectively. The devices were then annealed at 450 °C in nitrogen atmosphere for 30 min to fully activate the passivation capability of ALD-Al<sub>2</sub>O<sub>3</sub> thin films. Secondly, the photoresist (AZ 5214) patterns for ETL/Al were fabricated by photolithography and the corresponding Al<sub>2</sub>O<sub>3</sub> film above ETL patterns was removed by 4% HF. Thirdly, 1 nm MgO<sub>x</sub> film and 1 µm Al film were deposited by E-beam evaporation in sequence, and then the ETL/Al electrode was formed after lift-off process using acetone. Fourthly, a  $3-4\,\mu\text{m}$  photoresist patterns wrapped around the ETL/Al electrode was formed through photolithography, and the corresponding Al<sub>2</sub>O<sub>3</sub> thin film at the open regions was removed by 4% HF. At last, PEDOT:PSS (PH 1000 from Clevios) solution mixed with Triton-100 (0.25%) and dimethyl sulfoxide (5%) was spin coated on the rear side of device at a speed of 3000 rpm and annealed at 120 °C for 10 min, after that a 200 nm Ag film was deposited on the PEDOT:PSS film by E-beam evaporation.

#### 4.2. Front-back contact solar cells fabrication

Both of Front-PEDOT and Back-PEDOT devices in Fig. 2 used oneside randomly pyramids-textured wafers. After cleaning and removing native oxide, 5 nm a-Si:H(i) layer and 10 nm a-Si:H(n) were deposited on the polished-side for Front-PEDOT and pyramid-side for Back-PEDOT, respectively, through PECVD system. And then 200 nm Al was deposited on the a-Si:H layer by thermal evaporation for Front-PEDOT,



**Fig. 5.** Influence of gap passivation to PV properties of IBC-PEDOT solar cells. (a) Schematic illustration of holes transmission above gap region without passivation (left) and with passivation (right). (b–d) Simulation of  $J_{sc}$  (b),  $V_{oc}$  (c), PCE (d) as functions of  $S_{gap}$  and  $S_{ETL}$ . The pitch is 100  $\mu$ m, the yellow stars represent experimental data.

while 80 nm In<sub>2</sub>O<sub>3</sub>:W (IWO) film was deposited on the a-Si:H layer by reactive plasma deposition system for Back-PEDOT. After that, both of them were covered with PEDOT:PSS film. At last, a Ag grid electrode (200 nm) was thermally evaporated on the top side of both devices by a metal mask, and a 200 nm thick Ag film was deposited on the rear side of Back-PEDOT device. For the planar Front-PEDOT in Fig. 3, the processing flow is same as pyramid-texture Front-PEDOT solar cell except for the replacement of a-Si:H with E-Beam evaporated MgOx film as ETL.

## 4.3. Characterization

The morphological analysis of the samples was conducted by SEM (Hitachi S-4800) and TEM (Tecnai F20). Light J-V curves of solar cells were measured under a simulated AM 1.5 spectrum sunlight illumination and with a 0.5 cm<sup>2</sup> effective illumination area through a measurement mask. The reflectance spectra as well as the EQE were measured on the platform of quantum efficiency measurement (QEX10, PV Measurements), and we adjusted the beam spot of testing light to  $0.7 \times 0.7 \text{ cm}^2$  as well as added a white light bias of 0.1 Suns when we measured EQE. The I-V curves of contact resistance were measured by a Keithley 4200-scs semiconductor parameter analyzer. The minority carrier lifetime was measured by a microwave photoconductivity decay system (WT-2000 µPCD, Semilab).

#### 4.4. Simulation method

In the simulation, firstly, we utilized Lumerical Finite Difference Time Domain (FDTD) software to calculate 2D generation rate map of the entire structure of 200 µm thick silicon substrate. And there were two different top surface structure in simulation, one was pyramidstexture with 15 nm Al<sub>2</sub>O<sub>3</sub> and 60 nm SiN<sub>x</sub> and another was planar surface with 85 nm Al<sub>2</sub>O<sub>3</sub>. Secondly, the generation rate was introduced into the Lumerical DEVICE software, and through adjusting the recombination of each interface, we calculated a series of photovoltaic performance. In DEVICE simulation, the detailed parameters were set as following: Substrate was *n*-type silicon with 3 ms bulk lifetime and the dopant concentration was chosen as 10<sup>15</sup> cm<sup>-3</sup>. The diffusion parameters of  $p^{++}$  region were chosen as p-type dopant and the concentration was set at  $1 \times 10^{16}$  cm<sup>-3</sup>. This corresponds a  $V_{\rm bi}$  of 660 mV forming at the PEDOT/Si interface [29,30]. While the  $n^{++}$  region was set as *n*-type dopant with a concentration of  $1 \times 10^{15}$  cm<sup>-3</sup>. The surface recombination velocity of HTL/Si interface and front Al2O3/Si interface were set as 500 and 5 cm/s, respectively, according to the experimental results in Table S1.

## Acknowledgments

This work was supported by the National Natural Science Foundation of China (11674225, 11474201, and 61674154), Major State Basic Research Development Program of China (No. 2016YFB0700700), Zhejiang Provincial Natural Science Foundation (LR16F040002).

#### Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.nanoen.2018.06.013.

#### References

- [1] K. Yoshikawa, H. Kawasaki, W. Yoshida, T. Irie, K. Konishi, K. Nakano, T. Uto, D. Adachi, M. Kanematsu, H. Uzu, K. Yamamoto, Nat. Energy 2 (2017) 17032.
- [2] H.D. Um, N. Kim, K. Lee, I. Hwang, J.H. Seo, K. Seo, Nano Lett. 16 (2016) 981-987.
- W. Wu, W. Lin, J. Bao, Z. Liu, B. Liu, K. Qiu, Y. Chen, H. Shen, RSC Adv. 7 (2017) [3] 23851-23858.
- [4] J.P. Thomas, K.T. Leung, Adv. Funct. Mater. 24 (2014) 4978-4985.

- [5] Z. Wang, S. Peng, Y. Wen, T. Qin, Q. Liu, D. He, G. Cao, Nano Energy 41 (2017) 519-526
- [6] J. Bullock, M. Hettick, J. Geissbühler, A.J. Ong, T. Allen, Carolin M. Sutter-Fella, T. Chen, H. Ota, E.W. Schaler, S. De Wolf, C. Ballif, A. Cuevas, A. Javey, Nat. Energy 1 (2016) 15031.
- C. Battaglia, X. Yin, M. Zheng, I.D. Sharp, T. Chen, S. McDonnell, A. Azcatl, C. Carraro, B. Ma, R. Maboudian, R.M. Wallace, A. Javey, Nano Lett. 14 (2014) 967-971.
- [8] M. Biyour, J. Temmler, H. Steinkemper, M. Hermle, Sol. Energy Mater, Sol. Cells 142 (2015) 34-41.
- [9] G. Masmitjà, L.G. Gerling, P. Ortega, J. Puigdollers, I. Martín, C. Voz, R. Alcubilla, J. Mater. Chem. A 5 (2017) 9182-9189.
- [10] X. Yang, Q. Bi, H. Ali, K. Davis, W.V. Schoenfeld, K. Weber, Adv. Mater. 28 (2016) 5891-5897
- [11] X. Yang, K. Weber, Z. Hameiri, S. De Wolf, Prog. Photovolt.: Res. Appl. 25 (2017) 896-904.
- [12] Y. Wan, C. Samundsett, J. Bullock, M. Hettick, T. Allen, D. Yan, J. Peng, Y. Wu, J. Cui, A. Javey, A. Cuevas, Adv. Energy Mater. 7 (2017) 1601863.
- [13] J. Yu, Y. Fu, L. Zhu, Z. Yang, X. Yang, L. Ding, Y. Zeng, B. Yan, J. Tang, P. Gao, J. Ye, Sol. Energy 159 (2018) 704-709.
- [14] J. Bullock, P. Zheng, Q. Jeangros, M. Tosun, M. Hettick, C.M. Sutter-Fella, Y. Wan, T. Allen, D. Yan, D. Macdonald, S. De Wolf, A. Hessler-Wyser, A. Cuevas, A. Javey, Adv. Energy Mater. 6 (2016) 1600241.
- [15] D. Zielke, C. Niehaves, W. Lövenich, A. Elschner, M. Hörteis, J. Schmidt, Energy Procedia 77 (2015) 331-339.
- [16] J. He, P. Gao, Z. Yang, J. Yu, W. Yu, Y. Zhang, J. Sheng, J. Ye, J.C. Amine, Y. Cui, Adv. Mater. 29 (2017) 1606321.
- [17] J. He, Z. Yang, P. Liu, S. Wu, P. Gao, M. Wang, S. Zhou, X. Li, H. Cao, J. Ye, Adv. Energy Mater. 6 (2016) 1501793. [18] D. Zielke, A. Pazidis, F. Werner, J. Schmidt, Sol. Energy Mater. Sol. Cells 131 (2014)
- 110–116.
- [19] R. Gogolin, D. Zielke, A. Descoeudres, M. Despeisse, C. Ballif, J. Schmidt, Energy Procedia 124 (2017) 593-597.
- [20] S. Jackle, M. Mattiza, M. Liebhaber, G. Bronstrup, M. Rommel, K. Lips, S. Christiansen, Sci. Rep. 5 (2015) 13008.
- [21] C. Reichel, F. Granek, M. Hermle, S.W. Glunz, J. Appl. Phys. 109 (2011) 024507.
- [22] D.D. Smith, G. Reich, M. Baldrias, M. Reich, N. Boitnott, G. Bunea, 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), 2016, pp. 3351-3355.
- [23] L. He, C. Jiang, H. Wang, H. Lei, D. Lai, Rusli, Photovoltaic Specialists Conference, 42, 2012, pp. 002785-002787.
- [24] S. Jeong, M.D. McGehee, Y. Cui, Nat. Commun. 4 (2013) 2950.
- [25] P. Procel, M. Zanuccoli, V. Maccaronio, F. Crupi, G. Cocorullo, P. Magnone, C. Fiegna, J. Comput. Electron, 15 (2015) 260–268.
- [26] I. Cesar, N. Guillevin, A.R. Burgers, A.A. Mewe, M. Koppes, J. Anker, L.J. Geerligs, A.W. Weeber, Energy Procedia 55 (2014) 633-642.
- [27] P. Spinelli, B.W.H. van de Loo, A.H.G. Vlooswijk, W.M.M. Kessels, I. Cesar, IEEE J. Photovolt. 7 (2017) 1176-1183.
- [28] H. Tong, Z. Yang, X. Wang, Z. Liu, Z. Chen, X. Ke, M. Sui, J. Tang, T. Yu, Z. Ge, Y. Zeng, P. Gao, J. Ye, Adv. Energy Mater. (2018) 1702921. Y. Liu, Z.G. Zhang, Z. Xia, J. Zhang, Y. Liu, F. Liang, Y. Li, T. Song, X. Yu, S.T. Lee,
- [29] B. Sun, ACS Nano 10 (2016) 704–712.
- [30] Z. Yang, P. Gao, J. He, W. Chen, W.-Y. Yin, Y. Zeng, W. Guo, J. Ye, Y. Cui, ACS Energy Lett. 2 (2017) 556–562.



Hao Lin received his B.S. and M.S. degree in faculty of Science from Ningbo University, China, in 2010 and 2013, respectively. From 2012 to 2015, he worked in department of Physics and Materials Science, City University of Hong Kong, Currently, he is a Ph.D. candidate at School of Physics and Astronomy, Shanghai Jiao Tong University. His research interests include the solar energy materials, antireflection structure and dopant-free all-back-contact solar cells.



Dong Ding received his master degree in condensed matter physics of School of physics and engineering from Zhengzhou University, China, in 2016. He is currently a Ph.D. candidate in the School of Physics and Astronomy at Shanghai Jiao Tong University, China. His research interests focus on the simulation of solar cells, including the interdigitated back contact solar cells and related materials.



Zilei Wang received his B.S. degree in College of Physics and Information Engineering at Fuzhou University, China, in 2015. He is involved in a joint program between University of Science and Technology of China and Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences (CAS) in Ningbo, China. His research interests focus on organic-inorganic hybrid solar cells.



**Pingqi Gao** received Ph.D. degrees in Department of Physics from Lanzhou University in 2010. From 2007 to 2011, he worked in Nanyang Technological University as a visiting researcher and a research staff. In 2013, he joined Ningbo Institute of Materials Technology and Engineering, CAS, as an associate professor and then a professor (2015). His research focus on high efficiency solar cell technology, especially on developing new materials and processes for solar energy conversion. He has published over 70 journals.



Longfei Zhang received his B.S. degree in school of science from Shandong University of Technology, Zibo, China, in 2016. He is involved in a joint program between University of Science and Technology of China and Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences (CAS) in Ningbo, China. His research interests focus on dopant-free all-back-contact solar cells.



Jichun Ye received the B.S. degree in Materials Science and Engineering from University of Science and Technology of China in 2001 and the Ph.D. degree in Materials Science from University of California, Davis, USA in 2005. He joined Ningbo Institute of Material Technology and Engineering, CAS, as a professor and Ph.D. advisor since August of 2012. He was awarded for "Thousand Young Talents Program of China" in 2012. He has published more than 60 publications with nearly 500 times citations, applied more than 40 patents (including 10 awarded patents).



Fei Wu received the Bachelor degree in MinZu University of China, in 2016. She is currently a Master candidate in the School of Physics and Astronomy, Shanghai Jiao Tong University. Her research interests include solar energy materials and solar cells.



Wenzhong Shen received his Ph.D. degree in semiconductor physics and semiconductor device from Shanghai Institute of Technical Physics, Chinese Academy of Sciences, in 1995. Since 1999, Dr. Shen has been with Shanghai Jiao Tong University, China, as a full professor in the School of Physics and Astronomy, where he is currently the director of Institute of Solar Energy and Key Laboratory of Artificial Structures and Quantum Control, Ministry of Education.



Jing Yu received her B.S. degree in Material Forming and controlling Engineering from Shandong University, Shandong, China, in 2014. She is currently working toward the Ph.D. degree with the Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Science, Ningbo, China. Her research interests focus on high efficiency heterojunction solar cells with metal oxides as carrier-selective contacts.