Solution processed double-decked $V_{2}O_{x}$/PEDOT:PSS film serves as the hole transport layer of an inverted planar perovskite solar cell with high performance†

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In this paper, we have reported a high-performance inverted planar perovskite solar cell (PSC) with double-decked hole transport layer (HTL) sandwiched between the indium tinoxide (ITO) electrode and the perovskite photoactive layer. The double-decked HTL film is fabricated by coating inorganic vanadium oxide ($V_{2}O_{x}$) layer and poly(3,4-ethylenedioxythiophene)−poly(styrene sulfonate) (PEDOT:PSS) layer. In this study, double-decked $V_{2}O_{x}$/PEDOT:PSS HTL film can improve the optoelectronic properties of PSC device. It has been found that the double-decked $V_{2}O_{x}$/PEDOT:PSS film plays a crucial role in enhancing charge transfer rate and suppressing electron−hole pair recombination. The valence of vanadium in the $V_{2}O_{x}$ has been changed by adjusting the molar ratio of $V_{2}O_{5}$ to $H_{2}O_{2}$. The PSC can reach its best performance when $V_{2}O_{5}$ and $H_{2}O_{2}$ react at a molar ratio of 1:60. In addition, the concentration of the $V_{2}O_{x}$ aqueous solution has also been changed to optimize performance of PSC. Hence, the device with double-decked $V_{2}O_{x}$/PEDOT:PSS HTL film can increase the power conversion efficiency (PCE) to 15.86%, higher than that of reference device with PEDOT:PSS (13.56%). Besides, compared with reference device, our device has a better repeatability in the preparation process.

1. Introduction

Due to its excellent photo-electronic properties including low exciton binding energy (∼30 meV), high extraction coefficient (∼$10^{-3}$−$10^{-5}$ cm$^{-1}$), and long carrier diffusion lengths in thin films (>1 μm), the organic inorganic halide perovskite-based solar cell (PSC) have attracted considerable attention in the field of solar cells and made remarkable progress in recent years. Since 2009, the power conversion efficiency (PCE) of PSC has been increased from 3.8% to 22.1%,$^{10,11}$ which is unexpected and unprecedented in the field of organic photovoltaics. The PSC can be divided into two types: one with scaffold metal oxide layer and the other without the scaffold metal oxide layer like perovskite active layer sandwiched between the hole transport layer (HTL) and electron transport layer (ETL). The scaffold metal oxide layers have to be prepared under high-temperature conditions, such as $Al_{2}O_{3}$ or $TiO_{2}$ on indium tin oxide (ITO) or fluorine doped tin oxide (FTO). The planar heterojunction (PHJ) PSC without the scaffold metal oxide layer can also be classified into two categories: regular configuration (n−i−p, ETL/CH$_3$NH$_3$PbI$_3$−Cl/HTL) and inverted configuration (p−i−n, HTL/CH$_3$NH$_3$PbI$_3$−Cl/ETL). Owing to its low-temperature fabrication method, excellent performance and sharply-reduced hysteresis, PSC with inverted p−i−n structure will have a promising prospect in the future.

The poly(3,4-ethylenedioxythiophene)−poly(styrene sulfonate) (PEDOT:PSS) is usually used as HTL to enhance crystallinity of the perovskite layer film. We find it easy to collect the holes via the PEDOT:PSS layer, because PEDOT:PSS has many advantages over others such as high conductivity, smooth morphology, high work function (WF) and high transparency. The PCE of the inverted planar PSCs has been improved significantly by PEDOT:PSS HTL film. What merits much attention is that lots of research works have been carried out to enhance performances of PSCs, except PEDOT:PSS HTL film. Some researches have been conducted to use inorganic transition metal oxides including nickel oxide ($NiO_{x}$), lead sulfide (PbS), and molybdenum oxide ($MoO_{3}$) as the HTL film. The conduction levels of the oxides are much higher than the lowest occupied molecular orbital (LUMO) of the organic layers, which can prevent electrons from transporting in the wrong directions and improve the photo current of PSCs. However, most transition metal oxides films are thermally evaporated onto the substrates in vacuum and will hardly be applied to commercial production process of PSC devices due to its high cost.
Recently, some techniques based on a lower-cost, simpler and more controllable approach have been reported. Some solution-processed bilayer HTLs have been used in solar cells, such as graphene oxide (GO)/PEDOT:PSS, MoO3/PEDOT:PSS, and PEDOT:PSS/vanadium oxide (V2O5). Whereas, these cells do not show a higher performance. Here we use double-decked V2O5/PEDOT:PSS as HTL of PSCs, by contrast, the higher efficiency and better repeatability of the devices has been achieved by changing the valence of vanadium of double-decked V2O5/PEDOT:PSS film.

The vanadium pentoxide (V2O5) and its derivative compounds have been researched intensively due to their redox activity. The V2O5 can be obtained by a simple method of synthesis that uses V2O3 and hydrogen peroxide (H2O2) as starting material at a low temperature. Through this method, the vanadium element produces a variety of binary compounds with the chemical general formula VO2x (−0.5 ≤ x ≤ 0.5), such as V2O3, VO2, V2O5, V3O7, V4O9, V6O13. Likewise, the V2O5 with different valences can be prepared by controlling the molar ratio of V2O5 to H2O2. In this work, the double-decked V2O5/PEDOT:PSS films prepared by spin-coating V2O5 and PEDOT:PSS solution can serve as the HTL to enhance charge transfer rate and suppress electron–hole pair recombination in PSCs. Here we report a high-performance inverted planar PSC device with the structure of ITO/V2O5/PEDOT:PSS/CH3NH3PbI3/Ag. The maximum PCE of 15.86% has been achieved by controlling the optimum concentration of the V2O5 solution. An average power conversion efficiency (PCEAVG) of has been increased significantly from 11.85% (the PCEAVG of 30 reference devices with PEDOT:PSS HTL) to 14.97% (the PCEAVG of 120 controllable devices with the double-decked V2O5/PEDOT:PSS HTL).

2. Experimental

2.1 Materials and preparation

Chlorobenzene (C6H5Cl), hydrogen iodide (HI), methylamine (CH3NH2), hydrogen peroxide (H2O2, 30%) and V2O5 powder were purchased from Shanghai Chemical Industry Co. The PEDOT:PSS was bought from Heraeus (Germany). PbCl2 (99.999%) and N,N-dimethylformamide (DMF) (anhydrous, amine free; 99.9%) were purchased from Alfa-Aesar. The PCBM was produced by Nichem Fine Technology Co., Ltd. (Taiwan). CH3NH2I was synthesized by CH3NH2 and HI according to the reported procedure. CH3NH2PbI3–xClx solutions were fabricated by solubilizing CH3NH2 and PbCl2 in DMF with a molar ratio of 3:1, and agitating the compound in a glove box filled with N2 at 60 °C for 12 h. PCBM solutions were manufactured by dissolving PCBM powder in chlorobenzene and churning the mixture in a N2 glove box for 12 h, with an optimized concentration of 20 mg mL−1.

2.2 Fabrication of the double-decked V2O5/PEDOT:PSS film

First, V2O5 aqueous solution was manufactured by dissolving 15 mg of V2O5 powder in 5 mL of deionized water and churning the mixture in air at room temperature for 30 min, with a concentration of 3 mg mL−1. Second, the 0.6 mL of H2O2 aqueous solutions (30%) was added to V2O5 aqueous solution, the mixture was stirred for 10 min and let set for 10 h or more. As a result, the V2O5 aqueous solution was prepared. V2O5 aqueous solution prepared was filtered through a 0.22 μm pore-size filter membrane, spin-coated at 5000 rpm for 40 s on clean ITO substrates and dried at 150 °C for 10 min. Then, PEDOT:PSS solution filtered was spin-coated at 4500 rpm for 40 s on V2O5 films and dried at 140 °C for 20 min. Through this procedure, we have prepared a double-decked V2O5/PEDOT:PSS thin film with a thickness of about 40 nm.

2.3 Fabrication of the PSC device

13 × 15 mm ITO glass (Fine Chemicals Industry Co., Gyeonggi-do, Korea, 10 U sq−1) was patterned by the method mentioned. And the substrate etched was brushed by a cotton ball with detergent repeatedly. Then, in order to remove water-soluble and organic impurities on the substrate, we must clean ITO coated glass in deionized water, ethanol and acetone twice respectively, with ultrasonic for 15 min or more. After being washed, the substrate was dried in the dry box at 60 °C for 30 min and treated in UV-ozone cleaner for 10 min. Then the double-decked V2O5/PEDOT:PSS thin film was prepared on clean ITO coated glass through the method described above. To prepare the perovskite layer film, the CH3NH2PbI3–xClx solution was spin-coated onto the double-decked V2O5/PEDOT:PSS film layer at 4000 rpm for 40 s in a N2 glove box. The annealing of wet perovskite films was carried out by adopting a typical gradient increased temperature method that can be seen elsewhere. The substrates were slowly heated from 30 to 60 °C at a ramp rate of 10 °C/5 min and from 60 to 100 °C at a ramp rate of 10 °C/10 min on a hot plate, and the perovskite layer films were dried at 100 °C for 90 min. After that, PCBM film was deposited by spin-coating at 2000 rpm for 40 s onto perovskite layer film in a N2 glove box. Finally, the substrates were transferred to a vacuum chamber for silver electrode evaporation. The silver film was thermally deposited onto the PCBM film under vacuum at 4.5 × 10−5 Pa through a shadow mask, defining single device area of 6.25 mm2.

2.4 Characterizations

The surface and section morphology were characterized by a field emission scanning electron microscope (FESEM, Quanta 200 FEG, FEI Co.). The Energy dispersive spectroscopy (EDS) was carried out by an EDS device connected to FESEM. The atomic force microscope (AFM) images were collected by an Agilent 5500 SPM system (Agilent Technologies, USA). The crystalline phase and X-ray diffraction (XRD) patterns of perovskite films were recorded on a Rigaku D/MAX-2400 diffractometer. X-ray photoelectron spectroscopy (XPS) measurements were performed by using an AXIS Ultra instrument (Kratos UK) at a base pressure of ~10−8 Torr and 295 K. The WF of V2O5 films were measured through UPS (Riken Keiki). Steady-state photoluminescence (PL) measurements were conducted by using an Edinburgh FLS980 fluorescence spectrophotometer with an excitation at 470 nm. The current density–voltage (J–V) curves were measured (2400 Series Source...
In our study, V$_2$O$_5$ aqueous solution is prepared by the chemical reaction between V$_2$O$_5$ and H$_2$O$_2$, as mentioned in the experimental section. Probably, a process of the chemical reaction can be interpreted as follows: V$_2$O$_5$ powder is dissolved partially in deionized water at the beginning of chemical reaction process; the metal cations (V$^{5+}$) are generated by molecules of water. The reaction mentioned above is (eqn (1)).

$$V_2O_5 + H_2O \rightarrow V_2O_2 \cdot nH_2O$$ (1)

The reaction has increased acidity of the solution. The V$_2$O$_2 \cdot$ nH$_2$O molecule is dissociated by adding H$_2$O$_2$, forming the peroxovanadate. Therefore, the degree of acid hydrolysis is controlled by acidic precursor phase solution (eqn (2)).

$$V_2O_2 \cdot nH_2O + H_2O_2 \rightarrow H_3VO_4$$ (2)

The peroxovanadate is not very stable in aqueous solution. The partial stability of peroxovanadate in metastable phase is achieved when aqueous solution is let set for 10 h or more (partially oxidation of V$^{5+}$ to V$^{4+}$ ions), resulting in the formation a mixture of vanadium oxide (eqn (3)).

$$H_3VO_4 \rightarrow V_2O_4 \cdot nH_2O$$ (3)

XPS was used to investigate composition of the V$_2$O$_5$ thin film with the optimal molar ratio of V$_2$O$_5$ to H$_2$O$_2$. High resolution XPS spectrum corresponding to V is shown in Fig. 1a. As shown in the images, the V 2p spectrum can be well fitted with 2p$_{1/2}$ and 2p$_{3/2}$ doublets by a Gaussian function, which corresponds to vanadium in two different oxidation states (V$^{5+}$ and V$^{4+}$). Two peaks at the binding energy (BE) of 517.7 and 525.1 eV are corresponding to the 2p doublet of V$^{5+}$. And the other two peaks at the BE of 516.7 and 524.1 eV are correspond to 2p doublet of V$^{4+}$ respectively. The atomic concentration ratio of V$^{5+}$ to V$^{4+}$ is about 1.41 : 1 according to the area ratio of their peaks, implying that ~41.5% V$^{4+}$ exists in the V$_2$O$_5$ film layer. The V$^{4+}$ ions in V$_2$O$_5$ film could result in the enhancement of conductivity of the HTL, which facilitates the transport and collection of charge carrier in the PSC. EDS can qualitatively and quantitatively analyze all elements of the sample. The V$_2$O$_5$ solution is spin-coated on the polished monocrystalline silicon wafer rather than the ITO coated glass. The reason is that wafers have a lower roughness compared with the ITO film surface, which helps observe clearly the cross-section image of V$_2$O$_5$ film. As shown in Fig. 1b–d, the cross-section FESEM image together with vanadium elemental mapping and EDS spectrum are performed on V$_2$O$_5$ film based on monocrystalline silicon. The signals of V content of V$_2$O$_5$ film material were clearly observed. Moreover, it is important for us to point out that peaks of 2p$_{1/2}$ and 2p$_{3/2}$, which could lead to the rise in short-circuit current density ($J_{sc}$) enhancement the
extraction of the charge carriers from the absorption layer and reduction the carriers recombination.

In order to analyze the effect of different HTL films on the crystallization of CH\textsubscript{3}NH\textsubscript{3}PbI\textsubscript{3−x}Cl\textsubscript{x} thin films, we have measured the FESEM images of various HTL films and perovskite thin films based on HTL films. The surface FESEM images of V\textsubscript{2}O\textsubscript{x}, PEDOT:PSS and V\textsubscript{2}O\textsubscript{x}/PEDOT:PSS HTL films based on ITO coated glasses are shown in Fig. 3a–c, respectively. It is found that some particles with different sizes (the diameter ranges from 10 nm to 30 nm) are presented on surface of the V\textsubscript{2}O\textsubscript{x} film. The surfaces of ITO/PEDOT:PSS and ITO/V\textsubscript{2}O\textsubscript{x}/PEDOT:PSS films are more smooth than that of V\textsubscript{2}O\textsubscript{x} film, which will be more conducive to the growth of CH\textsubscript{3}NH\textsubscript{3}PbI\textsubscript{3−x}Cl\textsubscript{x} films. The AFM images of V\textsubscript{2}O\textsubscript{x}, PEDOT:PSS and V\textsubscript{2}O\textsubscript{x}/PEDOT:PSS HTL films are shown in Fig. S2a–c.† The surface roughness (root-mean-square, RMS) values of the V\textsubscript{2}O\textsubscript{x}, PEDOT:PSS and the V\textsubscript{2}O\textsubscript{x}/PEDOT:PSS HTL films are ∼5.7 nm, ∼3.3 nm and ∼2.5 nm, respectively. Compared with conventional PEDOT:PSS films, the V\textsubscript{2}O\textsubscript{x}/PEDOT:PSS film has a lower roughness. The roughness of the HTL film has a great influence on the morphology of perovskite films. Fig. 3d–f show surface FESEM images of CH\textsubscript{3}NH\textsubscript{3}PbI\textsubscript{3−x}Cl\textsubscript{x} thin films based on ITO/V\textsubscript{2}O\textsubscript{x}, ITO/PEDOT:PSS and ITO/V\textsubscript{2}O\textsubscript{x}/PEDOT:PSS films respectively. The V\textsubscript{2}O\textsubscript{x} film with different sizes of particles might be detrimental to the formation of crystal nucleus sites and the growth of crystalline grains, resulting in larger pores (the diameter of pores ranges from 50 nm to 300 nm) on the perovskite film surface based on ITO/V\textsubscript{2}O\textsubscript{x}. On the contrary, the pores of perovskite film based on ITO/PEDOT:PSS or ITO/V\textsubscript{2}O\textsubscript{x}/PEDOT:PSS are fewer and smaller, with the diameter of less than 50 nm. Furthermore, compared with the other two perovskite films, the film based on ITO/V\textsubscript{2}O\textsubscript{x}/PEDOT:PSS shows a larger crystal grains and more uniform surface topography, which results from the smoother V\textsubscript{2}O\textsubscript{x}/PEDOT:PSS HTL film.
The quenching of the PL emission by the V$_2$O$_3$ acceptors within the PSCs, steady-state PL measurements were carried out to investigate the quenching of perovskite emission. A explanation might be that oxygen deficiency close to the Fermi level of the material and reduction in doping in the perovskite film, although the photovoltaic performance of PSC device with double-decked PEDOT:PSS/HTL is used as reference device. For the device with double-decked PEDOT:PSS/V$_2$O$_3$ film, the $V_{OC}$ of it has been improved, its $J_{SC}$ and FF are lowered notably, resulting in its lower PCE. With the bias voltage increase, the current density experiences the process: slight decline—slight increase—rapid decline (Fig. 5a). For this strange phenomenon, we have not found a reasonable explanation. In order to compare the properties of different HTL materials, we fabricate three kinds of PSC devices with PEDOT:PSS, V$_2$O$_3$/PEDOT:PSS and PEDOT:PSS/V$_2$O$_3$ HTL films. The photoelectric properties of three PSCs are measured under the illumination of AM 1.5 G simulated solar light at 100 mW cm$^{-2}$. The $J$–$V$ curves of the PSC devices are shown in Fig. 5a. In our study, a conventional inverted PHJ PSC device with PEDOT:PSS HTL film is used as reference device. For the device with double-decked PEDOT:PSS/V$_2$O$_3$ film, the $V_{OC}$ of it has been improved, its $J_{SC}$ and FF are lowered notably, resulting in its lower PCE. With the bias voltage increase, the current density experiences the process: slight decline—slight increase—rapid decline (Fig. 5a). For this strange phenomenon, we have not found a reasonable explanation. A explanation might be that oxygen deficiencies close to the Fermi level of the material and reduction in doping in the perovskite film, result in the increase of current in the process of applying forward bias to PSC device with double-decked PEDOT:PSS/V$_2$O$_3$ film. Compared with reference device, the performances of PSC device with double-decked V$_2$O$_3$/PEDOT:PSS film have been significantly improved, such as the open circuit voltage ($V_{OC}$), $J_{SC}$, fill factor (FF) and PCE. The uniform and dense morphology of the perovskite film with

Fig. 4 The XRD spectra (a), the absorbance spectra (b) and the steady-state PL spectra (c) of the CH$_3$NH$_3$PbI$_3$–Cl$_x$ films after being annealed on the V$_2$O$_3$ film, the pristine PEDOT:PSS film, and the double-decked V$_2$O$_3$/PEDOT:PSS composite film, respectively.

Fig. 5 The $J$–$V$ curves (a), the dark $J$–$V$ curves (b) and the EIS spectra with the equivalent circuit (c) of PSCs based on the V$_2$O$_3$ film, the pristine PEDOT:PSS film, and the double-decked V$_2$O$_3$/PEDOT:PSS composite film, respectively.
double-decked V2Ox/PEDOT:PSS film (Fig. 3f) can effectively avoid defects and achieve a better performance.

To further understand the mechanism of performance improvement of PSCs with the double-decked V2Ox/PEDOT:PSS HTL, the $J$–$V$ curves (Fig. 5b) of three devices are recorded in the dark conditions. Dark current measurement is an effective method of evaluating the recombination of free carriers and charge carrier loss in the leakage pathways. It can be shown that the double-decked V2Ox/PEDOT:PSS and PEDOT:PSS/V2Ox could simultaneously prevent the leakage current under the condition of reverse bias and improve the current injection under the forward bias. Obviously, the smallest leakage current density and the largest rectification ratio are presented in the dark $J$–$V$ curve of the device with double-decked V2Ox/PEDOT:PSS at reverse-biased region, indicating a desired diode characteristics.

EIS measurements are performed to analyze the interfacial charge transfer process of devices. The Nyquist plots of three devices with different HTLs are shown in Fig. 5c. The frequency range measured is from $10^6$ to 1 Hz with AC amplitude of 10 mV at 0.84 V bias. Each impedance spectra is simulated through an equivalent circuit, forming a semicircle. The photovoltaic parameters of the devices are shown in Table 1, including series resistance ($R_s$), parallel resistance ($R_p$) and capacitance ($C$). It is found that $C$ is similar among three devices with different HTLs while their $R_p$ are changed regularly. The resistance of charge transport of the device with double-decked V2Ox/PEDOT:PSS film is the lowest. This indicates that charge transport rate of the device with double-decked V2Ox/PEDOT:PSS HTL film is the biggest among devices in this study.

The valence state of the vanadium element in the vanadium oxide has exerted a great influence on the conductivity of the HTL thin film and photoelectric properties of the PSC device. In our study, we change the valence of vanadium in the V2Ox by adjusting the molar ratio (1 : 20, 1 : 40, 1 : 60, 1 : 80 and 1 : 100) of V2O5 to H2O2. The photograph of various V2Ox solutions is shown in Fig. 6a. As the proportion of H2O2 increases, the color of the V2Ox solution gradually becomes light. The contents of V$^{4+}$ and V$^{5+}$ of the V2Ox thin film measured by XPS are shown in Table 2. The content of V$^{4+}$ increases with the ratio of H2O2, resulting in a higher conductivity of the double-decked V2Ox/PEDOT:PSS HTL film. As shown in Fig. 6b–e, the mean and standard deviations of the $V_{OC}$, $J_{SC}$, FF and PCE of PSC devices

| Devices | $R_s$ (Ω) | $R_p$ (kΩ) | $C$ (nF) |
|---------|-----------|-----------|----------|
| With PEDOT:PSS | 39.91 | 18.87 | 6.25 |
| With V2Ox/PEDOT:PSS | 43.17 | 13.08 | 7.36 |
| With PEDOT:PSS/V2Ox | 336.89 | 43.17 | 7.61 |

Table 2 The valence state contents of the V element of V2Ox thin film with different molar ratios of V2O5 to H2O2

| V element | Molar ratios of V2O5 to H2O2 |
|-----------|-----------------------------|
|           | 1 : 20 | 1 : 40 | 1 : 60 | 1 : 80 | 1 : 100 |
| V$^{4+}$  | 33.52% | 38.13% | 41.47% | 43.97% | 45.38% |
| V$^{5+}$  | 66.48% | 61.87% | 58.53% | 56.03% | 54.62% |

Fig. 6 (a) The photograph of the V2Ox solution prepared by mixing V2O5 and H2O2 at different molar ratios (1 : 20, 1 : 40, 1 : 60, 1 : 80 and 1 : 100). The mean and standard deviations of the $V_{OC}$ (b), $J_{SC}$ (c), FF (d) and PCE (e), and the $J$–$V$ curves (f) of the PSC devices with double-decked V2Ox/PEDOT:PSS HTL film with different molar ratios of H2O2 to V2O5.
with different molar ratios of H₂O₂ to V₂O₅ are calculated. It is found that the J_SC increases with molar ratio of H₂O₂ to V₂O₅. The conductivity of the double-decked V₂O₅/PEDOT:PSS HTL film improves with the increase of V⁴⁺, thus the J_SC of the device increases. However, the V_OC, FF and PCE show a trend—increase and then decline. Possibly, the decline of V⁵⁺ results in less doping and more defects of V₂O₅ thin film, as well as a lower performance of device. The best-performance (Fig. 6f) and high-reproducibility device is achieved when the molar ratio of V₂O₅ to H₂O₂ is 1 : 60, namely, the content of V⁴⁺ is 41.5%.

The concentration of V₂O₅ solution has a great influence on the thickness and uniformity of the double-decked V₂O₅/PEDOT:PSS HTL film. Therefore, we prepare V₂O₅ solutions with different concentration gradients (0.01, 0.02, 0.03, 0.04 and 0.05 M). The J–V characteristics of PSC based on pristine PEDOT:PSS and double-decked V₂O₅/PEDOT:PSS HTL film with varied concentration of V₂O₅ solution are shown in Fig. 7a. The Table 3 shows the key performance parameters of PSCs, including V_OC, J_SC, FF and PCE. The best performance of device is achieved under the concentration of 0.03 M of V₂O₅ solutions. With the increase of concentration of the V₂O₅ solution, all performance parameters of devices show a trend, that is, increase first and then decrease, except J_SC. The reason why J_SC keeps rising is that a higher concentration of V₂O₅ solution allows the V₂O₅ film to have a larger contact area with the PEDOT:PSS film. The thickness of the double-decked V₂O₅/PEDOT:PSS HTL film increases with concentration of V₂O₅ solution. On the one hand, when the concentration of V₂O₅ solution is very low, the V₂O₅ particles excessively disperse, failing to form the film. On the other hand, when the concentration of V₂O₅ solution gets very high, the film has a higher roughness. Moreover, there is a large barrier to extraction through the metal oxide valence band, because the V₂O₅/PEDOT:PSS layer is too thick to allow the tunnelling of charges. There is no doubt that these two aspects of the factors are not conducive to preparing high-performance devices. Fig. 7b shows the IPCE spectra of the PSCs based on pristine PEDOT:PSS and double-decked V₂O₅/PEDOT:PSS HTL film. Compared with the conventional AM 1.5 solar radiation spectrum,²⁷ interestingly, the IPCE of devices based on V₂O₅/PEDOT:PSS increases within a wide wavelength range between 500 and 700 nm, indicating that the devices with double-decked V₂O₅/PEDOT:PSS HTL can absorb more solar energy and convert it into electrical energy. In particular, the performance of the device with 0.03 M V₂O₅ is the best among devices.

The best performance of PSC device is achieved by controlling the optimal molar ratio of V₂O₅ to H₂O₂ and the concentration of the V₂O₅ solution. The J–V curve and main parameters (V_OC, J_SC, FF and PCE) of the best-performance device with the double-decked V₂O₅/PEDOT:PSS HTL film are shown in Fig. 8a. A best PCE of 15.86%, corresponding to a J_SC of 22.69 mA cm⁻², a V_OC of 0.93 V, and a FF of 0.75, is achieved. In our study, as shown in the histograms of PCE parameters of reference devices with PEDOT:PSS HTL (30 cells) (inset) and controllable devices with the double-decked V₂O₅/PEDOT:PSS HTL (120 cells).

Table 3 The main performance parameters of PSCs with varied concentration of V₂O₅ solution

| Devices | V_OC (V) | J_SC (mA cm⁻²) | FF      | PCE (%) |
|---------|----------|----------------|---------|---------|
| Reference | 0.92(0.91 ± 0.03) | 22.25(21.26 ± 1.07) | 0.72(0.67 ± 0.07) | 13.56(11.85 ± 1.81) |
| 0.01 M | 0.93(0.92 ± 0.02) | 22.15(21.23 ± 0.98) | 0.72(0.68 ± 0.06) | 14.95(13.53 ± 1.75) |
| 0.02 M | 0.94(0.93 ± 0.02) | 22.19(21.57 ± 0.75) | 0.73(0.71 ± 0.03) | 15.32(14.17 ± 1.17) |
| 0.03 M | 0.94(0.93 ± 0.01) | 22.41(21.96 ± 0.51) | 0.75(0.74 ± 0.02) | 15.86(14.97 ± 0.91) |
| 0.04 M | 0.93(0.92 ± 0.01) | 22.63(21.97 ± 0.89) | 0.74(0.73 ± 0.03) | 15.67(14.75 ± 0.99) |
| 0.05 M | 0.93(0.91 ± 0.04) | 23.12(21.99 ± 1.19) | 0.74(0.66 ± 0.09) | 15.18(13.98 ± 1.69) |
Fig. 8 (a) The J–V curve and main parameters of the best-performance device with the double-decked $V_2O_5$/PEDOT:PSS HTL film. (b) The histogram of PCEs of 120 double-decked $V_2O_5$/PEDOT:PSS HTL controlled devices. Inset is the histogram of PCEs of 30 reference devices with PEDOT:PSS HTL. (Gaussian distributions were fit to obtain the average and relative standard deviations.)

(Fig. 8b), the devices performance follows a Gaussian distribution and achieves the PCE_{AVE} of 11.85% and 14.97% respectively. The relative standard deviations of the reference devices and devices based on the $V_2O_5$/PEDOT:PSS are 9.8% and 4.5%, respectively, indicating that the latter shows a better reproducibility than the former.

4. Conclusions

With hard efforts we have successfully used solution-processed double-decked $V_2O_5$/PEDOT:PSS film as HTL of high-performance inverted planar PSCs. In our study, the best performance of the devices has been achieved by changing the valence of vanadium of double-decked $V_2O_5$/PEDOT:PSS film. Furthermore, the device performance has been optimized by controlling the optimum concentration of the $V_2O_5$ solution. The results show that the double-decked $V_2O_5$/PEDOT:PSS film plays an essential role in improving charge transfer rate and suppressing the electron–hole pair recombination. With this double-decked film, the PCE and reproducibility of PSCs have been improved significantly.

Acknowledgements

The authors gratefully acknowledge financial support from Natural Science Foundation of China (NSFC Grant No. 51502081), Doctoral Research Fund of Henan Normal University (No. 5101029170256), Science Funds for Young Scholar of Henan Normal University (No. 5101029279082).

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