Cd$_2$SnO$_4$ transparent conductive oxide: a promising alternative candidate for highly efficient hybrid halide perovskite solar cells†

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Introduction

In recent years, organic/inorganic perovskite hybrid photovoltaic devices have attracted considerable attention due to the abnormally excellent optical and electrical properties, such as ambipolar charge transport, high absorption coefficient, and wide band gap tunability, of perovskite materials.1–4 The power conversion efficiency has dramatically increased over the last few years. A PCE of up to 20% was obtained based on a p–i–n device architecture consisting of FTO/TiO$_2$/perovskite/HTM/Au via vacuum flash-assisted solution process.5 Note that these large-area perovskite devices show great potential for commercial application. For the p–i–n device architecture fabrication, the conventional devices have multiple layers including a front electrode, electron transport layer, perovskite layer, hole transport material (HTM) layer, and metal back electrode. Inverted planar heterojunction perovskite solar cells employ indium-doped-tin oxide, hole transport layer, perovskite layer, electron transport layer, and metal back electrode. The main research studies for investigating the performance of perovskite solar cells have been carried out on the interfacial modification,6–7 perovskite materials6–10 stability,11 etc. Improving the optical characteristics of the front electrode plays an important role in perovskite solar cells. However, the current sputtered transparent conductive oxides for perovskite solar cells are based on tin-doped indium-oxide and fluorine-doped tin oxide. It is necessary to find excellent transparent conductive oxide materials to realize high performance perovskite solar cells. Recently, other novel transparent conductive materials were employed as electrode layers to fabricate the perovskite-based hybrid solar cells, as shown in Table 1. The oxidized Ni/Au electrode was developed for perovskite solar cells with a conventional architecture, which exhibited potential applications for cost-effective, low weight, and stable solar cells.12 Copper nanowires as a vacuum-free and noble-metal-free transparent top electrode in perovskite solar cells were utilized and they exhibited promising device performance.13 Conducting polymers have been used as transparent electrodes to realize high efficiency, good flexibility, and low-cost perovskite planar heterojunction solar cells on flexible substrates.14–16 Highly transparent graphene, replacing the conventional transparent conductive oxide, had been applied in highly efficient perovskite solar cells.17

In addition, for conventional transparent conductive oxides used for commercial applications, the sheet resistance and
transmittance spectra of FTO do not show significant changes before and after thermal heating at 500 °C. Note that the electrical properties of ITO show significant changes as compared to those of FTO. This indicates that FTO shows relatively high stability against thermal heating. Therefore, ITO as a TCO layer to those of FTO. This indicates that FTO shows relatively high pyrolysis.

Cadmium stannate (Cd$_2$SnO$_4$) is a well-known transparent conductive oxide (TCO) that has been used in CdTe solar cells owing to its high electrical conductivity and optical transmission in the visible range compared to those of FTO. The thin film has demonstrated an electron mobility and resistivity of up to 100 cm$^2$ V$^{-1}$ s$^{-1}$ and 1.28 × 10$^{-4}$ Ω cm, respectively. It is a n-type semiconductor material with a band gap of around 3.0 eV, in which oxygen vacancies act as donor states. The conduction band edge position is closely matched with the conduction band minimum of TiO$_2$. The structure and optical characteristics of cadmium stannate thin films can be further tailored by gamma irradiation and suitable dopants, such as In and Sb. Furthermore, Cd$_2$SnO$_4$ thin films require cost-effective preparation techniques including radio frequency magnetron sputtering, sol-gel, dip coating, and spray pyrolysis. In addition to acquiring both high conductivity and stretch ability of the electrodes, Cd$_2$SnO$_4$ transparent conductive oxide renders these as excellent candidates for realizing high performance solar cells. However, serious issues of these materials cannot be ignored. Tin and cadmium are rare elements. Moreover, lead and cadmium components can cause serious environmental pollution. The material cost and toxicity should be considered for their application and commercialization in the future. Reducing the cost of the preparation process and reasonable device encapsulation should be carefully considered for rectifying these problems.

Herein, we exploited the Cd$_2$SnO$_4$ film to serve as a transparent conductive oxide for the Cd$_2$SnO$_4$/bl-TiO$_2$/mp-TiO$_2$/perovskite/spiro-MeOTAD/Au device. The presence of a Cd$_2$SnO$_4$ layer exhibited superior transmittance in the visible and NIR regions compared to the FTO substrate. Energy band diagram and interfacial features were discussed by constructing the thermal equilibrium energy band structure diagram from the vacuum energy level. Higher PCEs with an average of 15.58% under AM 1.5 irradiation for Cd$_2$SnO$_4$-based perovskite solar cells were obtained compared to those of the FTO-based devices. We believe that Cd$_2$SnO$_4$ film will be the most promising candidate for high performance perovskite solar cell applications.

### Experimental

#### Materials

Lead iodide, lead chloride, titanium diisopropoxide bis(acetylaceetone) (75% in isopropanol), and N,N-dimethylformamide were purchased from Alfa Aesar. Chlorobenzene was purchased from Acros. Spiro-MeOTAD was purchased from Lumtec. CH$_3$NH$_3$I was prepared using the method reported in literature. The conventional transparent conductive oxide substrate was FTO (Pilkington, thickness: 3.2 mm, sheet resistance 10 Ω per square). Cd$_2$SnO$_4$ thin films used as solar cell substrates were deposited by radio frequency magnetron sputtering on corning glass (sheet resistance: ~10 Ω per square).

#### Device fabrication

The devices Cd$_2$SnO$_4$ (and FTO)/bl-TiO$_2$/mp-TiO$_2$/CH$_3$NH$_3$I-PbI$_3$$_x$-Cl$_x$/spiro-OMeTAD/Au were fabricated. First, the transparent conductive oxide substrates were cleaned with a detergent. They were then sonicated with high purity water in an ultrasonic bath for 15 min, and then placed in boiling water for 5 min, and the abovementioned steps were repeated three times. TiO$_2$ blocking layer (bl-TiO$_2$) of 40 nm was prepared by spray pyrolysis using titanium diisopropoxide bis(acetylaceetone) (75% in isopropanol) (diluted in ethanol in a volumetric ratio of 1 : 40) at 450 °C. To prepare a 120 nm mesoporous TiO$_2$ layer (mp-TiO$_2$), diluted 18NR-T (Dyesol 18NR-T; ethanol = 2 : 15, m/m) was spin coated on the substrate at 4200 rpm for 40 s, and then annealed at 500 °C for 60 min. CH$_3$NH$_3$I was mixed with PbI$_2$ and PbCl$_2$ (mole ratio of PbI$_2$ : PbCl$_2$ : CH$_3$NH$_3$I = 1 : 1 : 4, 50 wt%) in DMF. Stirring at 65 °C and filtration led to transparent precursor solution. To obtain CH$_3$NH$_3$PbI$_3$$_x$-Cl$_x$ films, the precursor solution was spin-coated on the mp-TiO$_2$ layer at 4000 rpm for 50 s, and then placed in a drying cabinet for 50 min (at 20% relative humidity), followed by thermal annealing at 100 °C for 75 min. The spiro-MeOTAD layer was spin coated on the perovskite layer at 2000 rpm for 30 s from a hybrid solution (dissolved in chlorobenzene, 72 mg/1 mL; 17 μL Li-bis(trifluoromethanesulfonyl)-imide (Li-TFSI), dissolved in acetonitrile, 520 mg mL$^{-1}$ and 20 μL tert-butylpyridine (t-BP)). The gold film of 100 nm was deposited on the spiro-MeOTAD layer as the back electrode by thermal evaporation technology.

#### Characterization

The transmittance spectra were obtained using a Perkin Elmer Lambda 950 Spectrometer. The ultraviolet photoelectron spectroscopy (UPS) measurements of Cd$_2$SnO$_4$ film were performed using Thermo Scientific Escalab 250Xi. The SEM images were

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**Table 1** Reported transparent conductive materials in the references

| TCO | Device architecture | References |
|-----|---------------------|------------|
| Au:InO$_2$ | Au:InO$_2$/perovskite/Co$_9$/BCP/Al | 12 |
| PH1000 | PH1000/Pedot:PSS/perovskite/PCBM/Al | 14–16 |
| Graphene | Graphene/Mo$_2$O$_3$/Pedot:PSS/perovskite/Co$_9$/BCP/LiF/Al | 17 |
| Nanowires | FTO/TiO$_2$/perovskite/HTM/nanowires | 13 |
obtained using a Hitachi S-5200. Atomic force microscopy (AFM) measurements of the samples were conducted using Bruker multimode 8 scanning probe microscopy. The photo I–V curves were obtained using a Keithley 2400 Source meter under simulated AM 1.5G sunlight irradiation (100 mW cm⁻²) (ABET technologies Sun 2000 solar simulator). The light intensity was calibrated using a GaAs reference cell certified by NREL. The dark I–V curves were obtained using an Agilent 4284A precision LCR meter. The external quantum efficiency (EQE) was measured using a QEX10 measurement system (PV Measurements, Inc.). The active area of the devices was typically 0.15 cm². The steady-state and time-resolved photoluminescence spectra were obtained using a FLS 980 fluorescence spectrometer (Edinburgh Instruments) with excitation at 655 nm.

Results and discussion

The transmittance spectra of the FTO and Cd₂SnO₄ transparent conductive oxide substrates with a similar sheet resistivity of 10 Ω per square are illustrated in Fig. 1(a). Typically, to obtain a similar sheet resistivity with FTO, the thickness of the Cd₂SnO₄ film was controlled to ~250 nm during the sputter deposition process. As shown in Fig. 1(a), the Cd₂SnO₄ film showed better optical transmittance than the SnO₂:F film in the vis-NIR region. The onset of the transmittance spectra showed a slight difference due to difference in the optical band gap (Eg). According to the Tauc equation,²⁷

\[
ahv = A(hv - E_g)^n
\]

where a, A, and h represent the absorption coefficient, constant, and Planck constant, respectively. For a direct band gap semiconductor, n = 0.5, the optical band gap of Cd₂SnO₄ film can be calculated from eqn (1), as shown in Fig. 1(b). As is known, the optical band gap of a SnO₂:F film is 3.7 eV,²⁸ which is higher than that of a Cd₂SnO₄ film (~3.05 eV), leading to a slight red shift for the Cd₂SnO₄ film compared to the FTO substrate. It was observed that the transmittance in the 400–900 nm region of the Cd₂SnO₄ film was much better than that of the SnO₂:F film under similar sheet resistivity conditions. This suggests that thinner films will be required to obtain the same excellent optical properties (the thickness of ~400 nm for FTO). In addition, the transmittance of a Cd₂SnO₄ film at 1000 nm can still be up to ~86% compared to that of FTO (~80%). This also shows higher transmittance in the near-infrared region, which is of great benefit for the applications of perovskite-based tandem devices, such as monolithic perovskite/silicon tandem solar cells.²⁹–³¹

The UPS spectrum was obtained to calculate the work function of the Cd₂SnO₄ layer, as shown in Fig. 2. According to the linear fit at the secondary electron onset, we can obtain the sample inelastic cut-off (E_{cut-off}) of 17.02 eV. In the valence band emission region, the distance between the valence band (E_{VB}M) and Fermi edge (E_{Fermi}) can be estimated to 3.03 eV from the intercept of the linear fitting plot. Based on the Einstein’s photoemission law, the work function (Φ) can be described as follows:³²

\[
\Phi = hν - (E_{cut-off} - E_{Fermi})
\]

where hν represents the photon energy. The work function of the Cd₂SnO₄ film was calculated to be 4.2 eV. Based on the optical band gap from the transmittance spectra, the electron affinity (χ) can be written as

\[
χ = Φ + E_{VB}M - E_g
\]

According to eqn (3), we can obtain an χ value of 4.18 eV for the Cd₂SnO₄ film. This electron affinity for Cd₂SnO₄ film is comparable to that of FTO (4.4 eV [ref. 28]) transparent conductive oxide film. This indicates that the Cd₂SnO₄ film shows a compatible energy level for a transparent conductive oxide substrate.

To investigate the effect of energy band matching at the Cd₂SnO₄/TiO₂ interface, the thermal equilibrium energy band diagram of the Cd₂SnO₄/TiO₂ interface is shown in Fig. 3. Typically, the energy band parameters of TiO₂ are reported in another study.³³ The energy band parameters of the TiO₂ and Cd₂SnO₄ layers are listed in ESI Table S1.† In the front contact region of the photovoltaic devices, the electron-transporting layer/transparent conductive oxide layer interface has a key influence on electron collection. The high resistivity of the TiO₂ layer coated on the Cd₂SnO₄ layer provides reasonable electronic levels with favorable electron collection, associating with low recombination at the TiO₂/electrode interface.³⁴ As shown in Fig. 3, the work function of the TiO₂ layer is higher than that of Cd₂SnO₄ at the Cd₂SnO₄/TiO₂ interface, which renders it
possible for charge injection and collection from TiO$_2$ to the electrode. The energy band bending of 0.45 eV occurs in this heterojunction. The very small band barrier $D_n^c$ of 0.08 eV exists at the interface, enhancing the interfacial charge transport and decreasing the electronic re-ux and charge accumulation.

It is reasonable to form an energy band structure-matching between the Cd$_2$SnO$_4$ electrode and electron-transporting layer for an efficient charge transport process. This suggests that the Cd$_2$SnO$_4$ layer is a promising and excellent transparent conductive oxide substrate for TiO$_2$-based perovskite solar cells.

To investigate the effect of interfacial recombination on the Cd$_2$SnO$_4$ and TiO$_2$ layers, Cd$_2$SnO$_4$ (and FTO)/bl-TiO$_2$/spiro-OMeTAD/Au devices were prepared. Fig. 4(a–e) shows SEM and AFM images of the bl-TiO$_2$ on FTO and Cd$_2$SnO$_4$ substrates and the dark current density–voltage characteristics of the TCO/TiO$_2$/spiro-OMeTAD/Au devices. Their interface quality plays a key role in the performance of devices. As can be seen in Fig. 4(a–d), the morphology of TiO$_2$ is strongly dependent on the substrate. TiO$_2$ on the FTO substrate shows a large size compared to that on the Cd$_2$SnO$_4$ substrate. Highly dense and homogeneous TiO$_2$ films were formed by spray pyrolysis. AFM was carried out to study the morphology of different substrates. The AFM images of FTO and Cd$_2$SnO$_4$ substrates are shown in ESI Fig. S1. According to the AFM images, the surface root-mean-square (RMS) roughness of FTO, Cd$_2$SnO$_4$, FTO/TiO$_2$, and Cd$_2$SnO$_4$/TiO$_2$ were 12.2 nm, 7.24 nm, 8.16 nm, and 3.97 nm, respectively. The Cd$_2$SnO$_4$ and Cd$_2$SnO$_4$/TiO$_2$ layers show lower surface roughness as compared to the FTO substrate. Note that a smooth and compact TiO$_2$ coating layer can effectively be formed on the Cd$_2$SnO$_4$ substrate due to the smaller grain size of Cd$_2$SnO$_4$. As can be observed from the dark current density–voltage curves of TCO/TiO$_2$/spiro-OMeTAD/Au devices, the Cd$_2$SnO$_4$-based device shows a dark current density of $10^{-5}$ mA cm$^{-2}$, which is lower than that of the FTO-based device. This indicates that charge recombination can be decreased at the electron-transporting layer/Cd$_2$SnO$_4$ electrode interface. The higher surface roughness increases the interfacial charge recombination and reduces electron collection from the TiO$_2$ layer to the electrode.

Fig. 5(a and b) shows the typical structure configuration of perovskite device and the energy level alignment of the perovskite device employing the Cd$_2$SnO$_4$-based substrate. The glass/FTO/TiO$_2$/CH$_3$NH$_3$PbI$_3$/Cl$_x$/spiro-MeOTAD/Au devices were fabricated. The detailed preparation approaches are discussed in the methods section. The perovskite films absorb the incident photons under light irradiation, resulting in rapid generation, drift, and diffusion of excitons in the built-in electric field. Then, photoexcited charge transfer occurs at the TiO$_2$/perovskite/HTM interface. The holes of the valence band maximum position are extracted from the HOMO level of HTM. The electrons are
injected into the conduction band minimum position of the TiO₂ layer. Thus, the electrons are collected by the Cd₂SnO₄ electrode. The matching energy-band alignment can ensure smooth carrier transport between the TiO₂ and Cd₂SnO₄ electrode layers.

Fig. 5(c and d) shows cross-sectional SEM images of the FTO and Cd₂SnO₄-based devices. As can be seen in the two devices, the interfacial layers are effectively contacted to ensure charge transfer. These homogeneous and dense perovskite films fabricated using a high precursor concentration method were formed on the mp-TiO₂ layer. The morphology of the perovskite film has been reported in a previous study.⁴⁷ Compared to the cross-sectional SEM images of the two devices, the thickness of FTO substrate can be up to ~400 nm. As abovementioned, both substrates have a similar sheet resistivity of 10 Ω per square. The thickness of Cd₂SnO₄ substrate is only about 250 nm. This is important for regulating the film thickness of the front electrode, which presumably has an influence on the optical properties of the perovskite solar cells. A thicker transparent conductive oxide film decreases the optical transmittance and further affects the photovoltaic performance.

Fig. 6(a) shows the J–V curves of the FTO and Cd₂SnO₄-based devices obtained under an air mass 1.5 global irradiation of 100 mW cm⁻² for reverse and forward scanning. Table 2 lists the average photovoltaic parameters for the FTO and Cd₂SnO₄-based perovskite devices. Histograms of their device efficiency are shown in ESI Fig. S2.† Typically, the devices were investigated with a delay time of 10 ms from ~0.1 V to 1.1 V for the reverse and forward scanning direction. Both the FTO and Cd₂SnO₄-based devices exhibit slight hysteresis, as shown in Fig. 6(a), which is similar to the behavior of perovskite solar cells with a TiO₂ architecture reported in other studies possibly due to the unusual defect physics and grain boundary ion migration.⁴⁸–⁴⁹ The average photovoltaic performance parameters of the FTO-based device exhibit a PCE of 14.05%, open circuit voltage (Vₜₒ₉) of 0.97 V, short-circuit current density (Jₛ𝑐) of 20.04 mA cm⁻², and fill factor (FF) of 72.65% for the reverse scanning direction, and a Jₛ𝑐 of 19.14 mA cm⁻², Vₜₒ₉ of 0.90 V, FF of 70.2%, and PCE of 12.1% for the forward scanning direction. For the Cd₂SnO₄-based device, the performance shows a PCE of 15.58%, Vₜₒ₉ of 0.99 V, Jₛ𝑐 of 21.24 mA cm⁻², and FF of 73.83% for the reverse scanning direction, and a PCE of 14.06%, Vₜₒ₉ of 0.94 V, Jₛ𝑐 of 20.79 mA cm⁻², and FF of 72.2% for the forward scanning direction. As shown in Table 2, the Jₛ𝑐, Vₜₒ₉, and FF for the Cd₂SnO₄-based device are higher than those for the FTO-based device. Specifically, a higher photocurrent can be expected from the more incident photons absorbed by the perovskite film. Due to the high transmittance in the visible spectra region of the transparent conductive oxide layer, as shown in Fig. 1, more incident photons reach the perovskite layer from the front contact. More absorption and transition from the valence band to the conduction band occur in the photovoltaic layer. In addition, due to the high roughness of the FTO/TiO₂ interface, trapping states distributed in the energy band gap increase at the heterojunction interface, leading to an energy level offset that is deviated from the predicted level position.⁴¹ In this case, electron–hole recombination loss may occur due to the undesirable charge separation efficiency in the device, contributing to the lower Vₜₒ₉ and FF.⁴⁷ Fig. 6(b) shows the external quantum efficiency of the devices. The spectral response of the Cd₂SnO₄-based devices begins at ~320 nm, which exhibits narrow response compared to that of the FTO-based devices due to the lower optical energy band gap. This is consistent with the transmittance spectra, as shown in Fig. 1(a). The EQE dramatically increases in the 500–600 nm spectral range. This suggests that efficient charge extraction and transportation occur in the built-in electric field for the Cd₂SnO₄-based device, leading to a higher photogenerated current.

We further analyzed the I–V properties of the solar cells. According to the Shockley equation and equivalent circuit model for a single heterojunction solar cell, the I–V characteristic equation is described as follows:⁵⁰–⁵¹

\[
J = -J_{sc} + J_{0}\left\{ \exp \left[ \frac{e(V - J_{sc}R_{sh})}{nkT} - 1 \right] + \frac{V - J_{sc}R_{sh}}{R_{sh}} \right\} \tag{4}
\]

where \(J, J_{sc}, J_{0}, e, V, n, k, R_{sh}, R_{th}, T\) represent current density, short-circuit current density, recombination current density, electric charge, bias voltage, diode ideality factor, Boltzmann constant, series resistance, shunt resistance, and temperature, respectively. Based on the differential equation and mathematical conversion, eqn (4) can be written as

\[
\frac{dV}{dJ} = \frac{n}{e} \left( \frac{1 - R_{sh}}{J + J_{sc} - V/R_{sh}} \right) + R_{s} \tag{5}
\]

\[
\ln(J + J_{sc} - V/R_{sh}) = \frac{e}{nkT} (V - R_{s}J) + \ln J_{0} \tag{6}
\]

For perovskite devices, the shunt resistances of the devices are estimated to be 3000 Ω cm².⁴² The value of \(R_{s}\) is the intercept by linear curve fitting, as shown in Fig. 7(a). The series resistance of FTO and Cd₂SnO₄-based devices was estimated to be 1.63 Ω cm² and 1.46 Ω cm², respectively. This indicates that the Cd₂SnO₄-based device.
based device shows a lower series resistance due to the thickness of the films. Similarly, the value of $J_0$ can be obtained by linear curve fitting, as shown in Fig. 7(b). The values of the intercept for the FTO and Cd$_2$SnO$_4$-based devices are $-12.85$ and $-13.67$ and the recombination current density can be estimated to be $2.62 \times 10^{-6} \text{mA cm}^{-2}$ and $1.16 \times 10^{-6} \text{mA cm}^{-2}$, respectively. The lower $J_0$ of the Cd$_2$SnO$_4$-based devices indicates that interface charge recombination loss can be effectively decreased by interfacial engineering, leading to a higher $V_{oc}$ and FF.

The steady-state photoluminescence and time-resolved photoluminescence spectra were acquired to explore the photoinduced charge dynamical process in the devices. We prepared CH$_3$NH$_3$PbI$_{3-x}$Cl$_x$ films on FTO/TiO$_2$ and Cd$_2$SnO$_4$/TiO$_2$ substrates. Fig. 8(a) presents the steady-state photoluminescence spectra for CH$_3$NH$_3$PbI$_{3-x}$Cl$_x$ films on FTO/TiO$_2$ and Cd$_2$SnO$_4$/TiO$_2$ substrates. The PL intensity at 773 nm for the perovskite recombination of the free carriers in the perovskite is $0.55$ ns and the slow decay lifetime was $14.4$ ns, whereas the weight fractions were $67.7\%$ and $32.3\%$, respectively. This indicates that the decay of free charges was dominated by charge collection through the TiO$_2$/perovskite interface. However, the $\tau_1$ and $\tau_2$ for the Cd$_2$SnO$_4$/TiO$_2$/CH$_3$NH$_3$PbI$_{3-x}$Cl$_x$ sample decreased to $0.46$ ns and $9.26$ ns, respectively. The weight fraction of the fast decay component drastically increased to $89.6\%$. The Cd$_2$SnO$_4$ electrode facilitates faster charge transfer from perovskite to TiO$_2$. The electrode can enable the much faster and more efficient collection of the photogenerated electrons due to lower interfacial recombination loss as discussed above, leading to the enhancement of photovoltaic performance.

Furthermore, we investigated the long-term device stability of the Cd$_2$SnO$_4$-based device in a relative humidity of ~10% at room temperature, as shown in Fig. 9. The stability of the FTO-based device is shown in ESI Fig. S3.$^\dagger$

When the device was stored for 60 days, the $V_{oc}$ showed a slight decay. The device efficiency drops ~35% after 60 days. The FF and $J_{sc}$ of the device maintained 85% of its initial value. For the Cd$_2$SnO$_4$-based device, the FF and $J_{sc}$ of the device can retain ~95% of the initial value when the device was stored for 25 days. The dense HTM layer hinders the penetration of water molecule for a long time, which can improve the device stability. The device parameters did not show significant degradation in two months. However, the instability of perovskite devices is the main issue while exposing them to an ambient air environment. Moisture degradation and photooxidation may take place at the interface in the presence of oxygen, light, and moisture. Further enhancements of the stability of the device are required. Interface modification on TiO$_2$/CH$_3$NH$_3$PbI$_{3-x}$Cl$_x$ may be an effective method to improve the stability. In further studies, we believe that the introduction of surface treatment technology by passivation surface defects of TiO$_2$ layer to protect the perovskite devices from corrosion by moisture and oxygen is required. Solving the extrinsic and intrinsic degradation problem of the perovskite devices, which have potential for large scale applications, overcomes the major obstacles in their practical applications.

**Conclusion**

We demonstrated a new structure of perovskite solar cell using a Cd$_2$SnO$_4$ transparent conducting oxide substrate. Owing to
its higher electrical conductivity, optical transmission in the visible range, and lower surface roughness as compared to those of FTO, a higher PCE of 15.58% for the Cd$_2$SnO$_4$-based perovskite solar cell was obtained. The energy band structure and interfacial characteristics of Cd$_2$SnO$_4$/TiO$_2$ interface were investigated. The results showed that the matching energy band alignment could ensure smooth carrier transport and collection between the TiO$_2$ and Cd$_2$SnO$_4$ electrode layers, which suggests that Cd$_2$SnO$_4$ transparent conducting oxide would be the most promising candidate for high performance perovskite solar cells.

Acknowledgements

This work was financially supported by the Science and Technology Program of Sichuan Province (No. 2016GZX0272) and the Innovation Program of Sichuan University (No. 201510611374, No. 201510610799 and No. 201510610437).

References

1 D. P. McMeeking, G. Sadoughi, W. Rehman, G. E. Eperon, M. Saliba, M. T. Horannter, A. Haghighirad, N. Sakai, L. Korte, B. Rech, M. B. Johnston, L. M. Herz and H. J. Snaith, Science, 2016, 351, 151–153.
2 D. Bi, W. Tress, M. I. Dar, P. Gao, J. Luo, C. Renerve, K. Schenk, A. Abate, F. Giordano, J. P. Correa Baena, J. D. Decoppe, S. M. Zakeeuddin, M. K. Nazeeruddin, M. Gratzel and A. Hagfeldt, Sci. Adv., 2016, 2, e1501170.
3 D. Liu, L. Wu, C. Li, S. Ren, J. Zhang, W. Li and L. Feng, ACS Appl. Mater. Interfaces, 2015, 7, 16330–16337.
4 Q. Tai, P. You, H. Sang, Z. Liu, C. Hu, H. L. W. Chan and F. Yan, Nat. Commun., 2016, 7, 11105.
5 X. Li, D. Bi, C. Yi, J.-D. Decoppe, J. Luo, S. M. Zakeeuddin, A. Hagfeldt and M. Grätzl, Science, 2016, 353, 58–62.
6 Z. Zhou, J. Xu, L. Xiao, J. Chen, Z. A. Tan, J. Yao and S. Dai, RSC Adv., 2016, 6, 78585–78594.
7 L. F. Zhu, Y. Z. Xu, J. J. Shi, H. Y. Zhang, X. Xu, Y. H. Zhao, Y. H. Luo, Q. B. Meng and D. M. Li, RSC Adv., 2015, 6, 82282–82288.
8 Z. Zhang, X. Yue, D. Wei, M. Li, P. Fu, B. Xie, D. Song and Y. Li, RSC Adv., 2015, 5, 104606–104611.
9 D. Liu, C. Liu, L. Wu, W. Li, F. Chen, B. Xiao, J. Zhang and L. Feng, RSC Adv., 2015, 5, 119204–119209.
10 X. Xia, W. Wu, H. Li, B. Zheng, Y. Xue, J. Xu, D. Zhang, C. Gao and X. Liu, RSC Adv., 2016, 6, 14792–14798.
11 H. Sohrabpoor, G. Puccetti and N. E. Gorji, RSC Adv., 2016, 6, 49328–49334.
12 W.-C. Lai, K.-W. Lin, Y.-T. Wang, T.-Y. Chiang, P. Chen and T.-F. Guo, Adv. Mater., 2016, 28, 3290–3297.
13 H. Hwang, A. Kim, Z. Zhong, H.-C. Kwon, S. Jeong and J. Moon, Adv. Funct. Mater., 2016, 26, 6545–6554.
14 M. Dianetti, F. Di Giacomo, G. Polino, C. Ciceroni, A. Liscio, A. D’Epifanio, S. Licoccia, T. M. Brown, A. Di Carlo and F. Brunetti, Sol. Energy Mater. Sol. Cells, 2015, 140, 150–157.
15 Y. Li, L. Meng, Y. M. Yang, G. Xu, Z. Hong, Q. Chen, J. You, G. Li, Y. Yang and Y. Li, Nat. Commun., 2016, 7, 10214.
16 K. Sun, P. C. Li, Y. J. Xia, J. J. Chang and J. Y. Ouyang, ACS Appl. Mater. Interfaces, 2015, 7, 15314–15320.
17 H. Sung, N. Ahn, M. S. Jang, J.-K. Lee, H. Yoon, N.-G. Park and M. Choi, Adv. Energy Mater., 2016, 6, 1501873.
18 J. A. Stove, J. D. Beach, W. C. Bradford and T. R. Ohno, Thin Solid Films, 2014, 562, 254–259.
19 X. Wu, Sol. Energy, 2004, 77, 803–814.
20 B. A. Korevaar, J. R. Cournoyer, O. Sulima, A. Yamikov and J. N. Johnson, Prog. Photovoltaics Res. Appl., 2014, 22, 1040–1049.
21 S. Al-Sofiany and H. E. Hassan, J. Alloys Compd., 2015, 651, 149–156.
22 R. Kumaravel and K. Ramamurthi, J. Alloys Compd., 2011, 509, 4390–4393.
23 R. Mamazza, D. L. Morel and C. S. Fereiken, Thin Solid Films, 2005, 484, 26–33.
24 G. Valincius, V. Reipa, V. Vilker, J. T. Woodward and M. Vaudin, J. Electrochem. Soc., 2001, 148, E341–E347.
25 R. B. H. Tahar, T. Ban, Y. Ohya and Y. Takahashi, J. Am. Ceram. Soc., 2001, 84, 85–91.
26 J. H. Im, I. H. Jang, N. Pellet, M. Gratzel and N. G. Park, Nat. Nanotechnol., 2014, 9, 927–932.
27 J. Tauc, Mater. Res. Bull., 1968, 3, 37–46.
28 M. A. Green, A. Ho-Baillie and H. J. Snaith, Nat. Photonics, 2014, 8, 506–514.
29 J. Wern, C.-H. Weng, A. Walter, L. Fesquet, J. P. Seif, S. De Wolf, B. Niesen and C. Ballif, J. Phys. Chem. Lett., 2016, 7, 161–166.
30 T. Duong, N. Lal, D. Grant, D. Jacobs, P. Zheng, S. Rahman, H. Shen, M. Stocks, A. Blakers, K. Weber, T. P. White and K. R. Catchpole, IEEE J. Photovolt., 2016, 6, 679–687.
31 J. Wern, G. Dubuis, A. Walter, P. Löper, S.-J. Moon, S. Nicolay, M. Morales-Masios, S. De Wolf, B. Niesen and C. Ballif, Sol. Energy Mater. Sol. Cells, 2015, 141, 407–413.
32 Y. Park, V. Choong, Y. Gao, B. R. Hsieh and C. W. Tang, Appl. Phys. Lett., 1996, 68, 2699–2701.
33 A. Dymshits, A. Henning, G. Segev, Y. Rosenwaks and L. Litg, Sci. Rep., 2015, 5, 8704.
34 J. Shi, X. Xu, D. Li and Q. Meng, Small, 2015, 11, 2472–2486.
35 Z. Zhou, S. Pang, Z. Liu, H. Xu and G. Cui, J. Mater. Chem. A, 2015, 3, 19205–19217.
36 G. Xing, B. Wu, S. Chen, J. Chua, N. Yantara, S. Mhaisalkar, N. Mathews and T. C. Sun, Small, 2015, 11, 3606–3613.
37 D. Liu, C. Liu, L. Wu, W. Li, F. Chen, B. Xiao, J. Zhang and L. Feng, RSC Adv., 2016, 6, 28719–28724.
38 S. Wozny, M. Yang, A. M. Nardes, C. C. Mercado, S. Ferrere, M. O. Reese, W. Zhou and K. Zhu, Chem. Mater., 2015, 27, 4814–4820.
39 H.-S. Kim and N.-G. Park, J. Phys. Chem. C, 2014, 5, 2927–2934.
40 Y. Shao, Y. Fang, T. Li, Q. Wang, Q. Dong, Y. Deng, Y. Yuan, H. Wei, M. Wang, A. Gruverman, J. Shield and J. Huang, Energy Environ. Sci., 2016, 9, 1752–1759.
41 Q.-K. Wang, R.-B. Wang, P.-F. Shen, C. Li, Y.-Q. Li, L.-J. Liu, S. Duhm and J.-X. Tang, Adv. Mater. Interfaces, 2015, 2, 1400528.
42 J. Shi, J. Dong, S. Lv, Y. Xu, L. Zhu, J. Xiao, X. Xu, H. Wu, D. Li, Y. Luo and Q. Meng, Appl. Phys. Lett., 2014, 104, 063901.
43 J. Qing, H.-T. Chandran, Y.-H. Cheng, X.-K. Liu, H.-W. Li, S.-W. Tsang, M.-F. Lo and C.-S. Lee, ACS Appl. Mater. Interfaces, 2015, 7, 23110–23116.
44 P.-W. Liang, C.-Y. Liao, C.-C. Chueh, F. Zuo, S. T. Williams, X.-K. Xin, J. Lin and A. K. Y. Jen, Adv. Mater., 2014, 26, 3748–3754.
45 Y. Shi, Y. Xing, Y. Li, Q. Dong, K. Wang, Y. Du, X. Bai, S. Wang, Z. Chen and T. Ma, J. Phys. Chem. C, 2015, 119, 15868–15873.