



Solid state p-type dye sensitized NiO–dye–TiO₂ core–shell solar cells†

Lei Tian,^a Jens Föhlinger,^{ib} Zhibin Zhang,^b Palas Baran Pati,^a Junzhong Lin,^c Tomas Kubart,^{ib} Yong Hua,^{id} Junliang Sun,^c Lars Kloo,^d Gerrit Boschloo,^a Leif Hammarström^a and Haining Tian^{ib} *^a

Cite this: *Chem. Commun.*, 2018, 54, 3739

Received 20th January 2018,
Accepted 19th March 2018

DOI: 10.1039/c8cc00505b

rsc.li/chemcomm

Solid state p-type dye sensitized NiO–dye–TiO₂ core–shell solar cells with an organic dye PB6 were successfully fabricated for the first time. With Al₂O₃ as an inner barrier layer, the recombination process between injected holes in NiO and injected electrons in TiO₂ was significantly suppressed and the charge transport time was also improved.

p-Type dye sensitized solar cells (p-DSCs) have attracted intense interest due to their different charge transfer kinetics with respect to more common studied n-DSCs,^{1–3} and the potential application in tandem solar cells^{4–6} and solar fuel devices.^{7–9} The conventional p-DSCs are based on liquid redox electrolytes. To avoid having a liquid phase in the p-DSCs, we have recently proposed and proven the concept of solid state p-DSCs, in which a solid state phenyl-C61-butyric acid methyl ester (PCBM) was used as an electron transport material (ETM) between the dye sensitized photocathode and the back contact.¹⁰ Optimization of photosensitizer represents one strategy to improve the performance of this kind of solar cells.^{11,12} Inspired by the conventional dye sensitized TiO₂ solar cells, we proposed that TiO₂ should be an alternative ETM to PCBM due to the fast electron injection from dyes into TiO₂^{13,14} and good electron transport property.¹⁵ Thus, we recently fabricated a dye sensitized NiO–dye–TiO₂ core–shell film and, in contrast to previous work,^{16–18} the nanoporous NiO film was first sensitized with the dye and a TiO₂ coating was applied afterwards. This dye sensitized core–shell film showed ultrafast hole ($t_{1/2} < 120$ fs) and electron injection into NiO and TiO₂ respectively, resulting in ultrafast dye regeneration upon electron injection, $t_{1/2} \leq 500$ fs.¹⁹ In the present work, we proved that the dye sensitized NiO–dye–TiO₂ core–shell mesoporous film can be used for fabrication of solid

state p-type dye sensitized solar cells. We also show the effect of an Al₂O₃ inner barrier layer between NiO and TiO₂ on the performance of solar cell.

Fig. 1 shows the configuration and working principle of the proposed p-type dye sensitized NiO–dye–TiO₂ core–shell solar cells. The donor– π –acceptor dye PB6 was utilized as photosensitizer since its reduction/oxidation potentials in excited state match with the valence band of NiO and conduction band of TiO₂.¹⁹

The fabrication of the photoelectrode used in this study can be described briefly as follows. A compact NiO layer (60 nm) was sputtered onto a FTO substrate, then a mesoporous NiO layer (1.3 μm) was prepared by doctor-blading NiCl₂ gel on FTO glass and sintered at 450 °C for 0.5 h.²⁰ Subsequently, the NiO electrode was immersed into 0.2 mM PB6 dichloromethane (DCM) solution overnight. The dye loading in the film was determined to be 31.6 nmol cm^{–2} by desorption experiment (see ESI†). After rinsing with methanol, the dye sensitized NiO film was dried and coated with metal oxides by atomic layer deposition (ALD). For NiO–PB6–TiO₂ photoelectrode, ca. 10 nm TiO₂ layer was coated directly on a dye sensitized NiO film. Because an insulating Al₂O₃ layer has been proved to be an effective barrier to suppress charge recombination process in DSCs,^{21–24} an 1 nm inner Al₂O₃ layer was introduced by ALD on the dye sensitized NiO film, followed by deposition of ca. 10 nm TiO₂ coating to form NiO–PB6–Al₂O₃–TiO₂ photoelectrode.

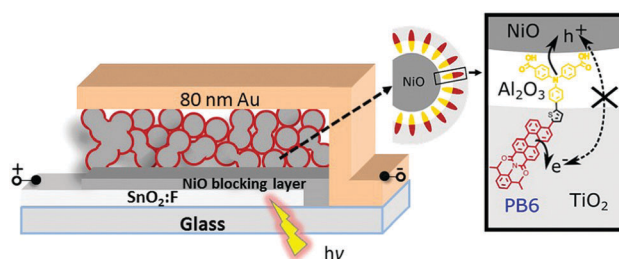


Fig. 1 The configuration and working principle of the p-type dye sensitized NiO–dye–TiO₂ core–shell solar cell, NiO–PB6–Al₂O₃–TiO₂, with Al₂O₃ as an inner barrier layer and PB6 dye as photosensitizer.

^a Department of Chemistry–Ångström Lab., Uppsala University, Sweden.
E-mail: haining.tian@kemi.uu.se

^b Department of Engineering Sciences, Uppsala University, Sweden

^c Department of Materials and Environmental Chemistry, Stockholm University, Sweden

^d Department of Chemistry, KTH Royal Institute of Technology, Sweden

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c8cc00505b



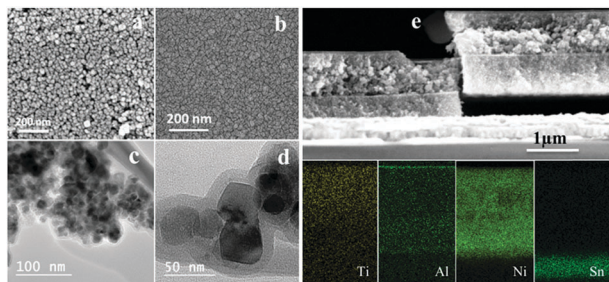


Fig. 2 SEM and TEM figures of the **NiO-PB6-Al₂O₃-TiO₂** sample. (a and b) SEM surface images before and after ALD; (c and d) TEM images in different magnification; (e) SEM image in the cross section and the corresponding EDX element mapping analysis.

In addition, we prepared two reference samples without dye sensitization, denoted **NiO-TiO₂** and **NiO-Al₂O₃-TiO₂**, respectively, to exclude the potential photovoltaic performance from the excitation of the p-n junction formed at the interface of NiO and TiO₂.

In previous work, we have shown that the TiO₂ layer penetrated into the dye sensitized mesoporous NiO electrode. In order to monitor the penetration of Al₂O₃ into the dye sensitized mesoporous NiO electrode, as well as TiO₂ into the Al₂O₃ coated electrode afterwards, the morphology of **NiO-PB6-Al₂O₃-TiO₂** photoelectrode with 1 nm Al₂O₃ (calculated from the average ALD deposition rate from multi-cycles) was characterized by SEM and TEM (Fig. 2). A more compact surface (Fig. 2b) was observed after subsequent ALD of Al₂O₃ and TiO₂ compared to the mesoporous dye sensitized NiO film (Fig. 2a). From TEM images in Fig. 2c and d, one can note that NiO nanoparticles are coated by a conformal layer, which is assigned to TiO₂ and Al₂O₃ layers. From EDX elements analysis images of the cross section of the electrode, the presence of Al and Ti inside the NiO mesoporous layer was confirmed, signifying that Al₂O₃ can penetrate into the mesoporous NiO film and that the thin Al₂O₃ layer does not block the TiO₂ penetration.

In order to confirm the potential application of these core-shell photocathodes in solar cells, an 80 nm Au layer was thermally evaporated on the top of these electrodes as back contact to complete the solar cell. The performance of such solar cells was characterized under AM 1.5 G illumination with light intensity of 100 mW cm⁻² and the *J-V* curves are shown in Fig. 3a. A short-circuit current density (*J*_{sc}) of 12 μA cm⁻² and an open-circuit voltage (*V*_{oc}) of 0.40 V were obtained in **NiO-PB6-TiO₂** solar cell. The device based on **NiO-TiO₂** film without PB6 dye was also fabricated and showed photovoltaic effect, resulting from the p-n junction of **NiO-TiO₂** due to the direct contact between NiO and TiO₂. From Incident Photon-to-Current Efficiency (IPCE) spectra (Fig. 3b), we can note that the PB6 dye in **NiO-PB6-TiO₂** solar cell has light response in wavelength from 480 nm to 700 nm, which is in agreement with the dye absorption spectrum (Fig. S2, ESI[†]), proving that the photocurrent is generated by dye. IPCE curve of the **NiO-TiO₂** solar cell abruptly decreases to zero at wavelengths higher than 500 nm (2.48 eV), and only small part of the visible light can be converted into photocurrent in these solar cells. By using 1 nm Al₂O₃ to coat NiO, the **NiO-TiO₂** p-n junction structure in **NiO-Al₂O₃-TiO₂** was inhibited and the solar cell did

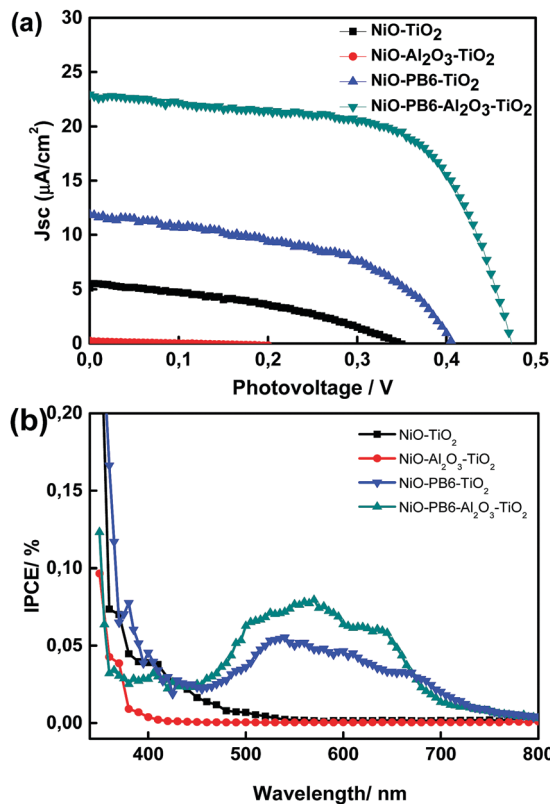


Fig. 3 *J-V* curves and IPCE of different dye sensitized p-type core-shell solar cells and reference solar cells.

not render any distinguishable photocurrent from *J-V* and IPCE characterization (see Fig. 3a and b). The same strategy was adopted in a **NiO-PB6-Al₂O₃-TiO₂** solar cell, in which Al₂O₃ could also act as a blocking layer to suppress the charge recombination between injected holes from dye in NiO and injected electrons from dye in TiO₂. As the molecular extension of the PB6 dye was estimated to be ca. 2.5 nm, a 1 nm Al₂O₃ layer should not completely cover the electron donor unit of the PB6 dye, assuming the standing dye configuration on the metal oxide surface. It should provide an opportunity for the TiO₂ layer to fully cover the dye acceptor unit and collect the electrons. Noticeably, the photovoltaic performance of the **NiO-PB6-Al₂O₃-TiO₂** solar cell was significantly improved compared to the device without Al₂O₃, showing a *J*_{sc} of 23 μA cm⁻² and a *V*_{oc} of 0.48 V, and higher IPCE values in visible region. Meanwhile, a fill factor (FF) of 66% was achieved in the **NiO-PB6-Al₂O₃-TiO₂** solar cell, which is the highest FF reported³ in p-type DSCs to our best knowledge (Table S1, ESI[†]).

To further elucidate the electron and hole injection in **NiO-PB6-Al₂O₃-TiO₂** electrode, femtosecond transient absorption spectroscopy was carried out (Fig. S3, ESI[†]). A pronounced Stark effect was observed upon light excitation, resulting from dye regeneration after hole and electron injection from dye into NiO and TiO₂ respectively. The dye regeneration time in **NiO-PB6-Al₂O₃-TiO₂** is *t*_{1/2} ≤ 500 fs. These are consistent with our previous study of **NiO-PB6-TiO₂**,¹⁹ signifying that the Al₂O₃ layer essentially did not affect the dye regeneration rate. Meanwhile, the same kinetic behaviour as **NiO-PB6** reported



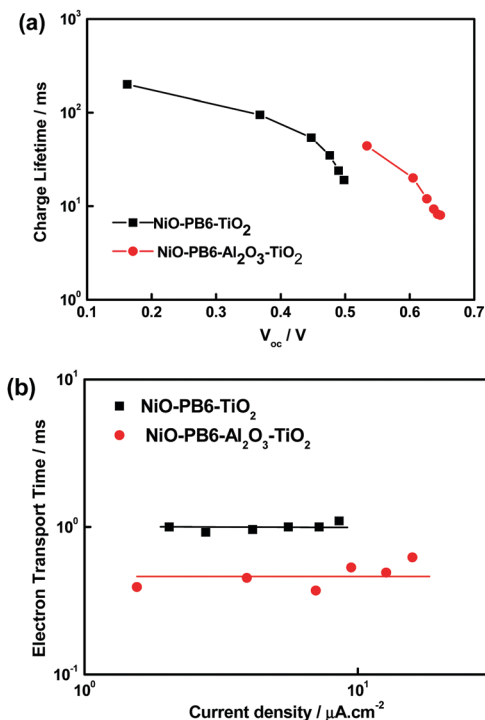


Fig. 4 Electron lifetime as a function of V_{oc} and transport time as a function of photocurrent density of NiO-PB6-Al₂O₃-TiO₂ and NiO-PB6-TiO₂.

in our previous study¹⁹ was found in NiO-PB6-Al₂O₃ (Fig. S4, ESI[†]), further confirming that the Al₂O₃ layer did not significantly influence hole injection.

In order to gain insight into the effect of the Al₂O₃ layer on the charge recombination process in solar cells, charge lifetimes as a function of V_{oc} of the solar cells were measured (Fig. 4a). It shows that NiO-PB6-Al₂O₃-TiO₂ solar cell has longer charge lifetime than NiO-PB6-TiO₂ solar cell at a given V_{oc} value. From charge extraction experiments (Fig. S5, ESI[†]), two types of solar cells show almost identical extracted charges at a specific V_{oc} , implying that the Al₂O₃ layer does not influence the energy band position in either NiO or ALD TiO₂. These results suggest that the Al₂O₃ layer indeed plays the role of an inner barrier layer in suppressing charge recombination between NiO and TiO₂, thus contributing to the enhanced V_{oc} and increased J_{sc} .

Interestingly, the charge transport time (Fig. 4b) of the NiO-PB6-Al₂O₃-TiO₂ solar cell is shorter than that of the NiO-PB6-TiO₂ solar cell. We suggest that the TiO₂ formed in the presence of Al₂O₃ is more compact due to the more hydrophilic properties after ALD Al₂O₃ (the existence of -OH units on the ALD Al₂O₃ surface). TiO₂ of better quality is expected to be grown on the more hydrophilic surface during ALD in contrast to the NiO surface sensitized with an organic dye,²⁵ although the amorphous structure in both samples is confirmed by TEM. The shorter charge transport time in NiO-PB6-Al₂O₃-TiO₂ solar cell should be responsible for higher J_{sc} and higher fill factor as compared to the NiO-PB6-TiO₂ solar cell. Notably, the charge transport times of both types of solar cells are almost independent of the photocurrent (light intensity), which is unusual for the conventional n-type and p-type DSCs.^{26,27}

One possible explanation is that the TiO₂ phase is not continuous inside the mesoporous NiO film (1.3 μm), resulting in that only a very thin NiO film coated by ALD TiO₂ works for the charge collection. Another explanation would be that holes and/or electrons transferred *via* the semiconductor surfaces.²⁸ The former one can also be applied to explain why the photocurrent is much lower than the conventional p-DSCs, although the dye regeneration in the core-shell solar cell is much faster¹⁹ and the charge lifetime is comparable to those p-DSCs.^{26,29} Therefore, making continuous TiO₂ layer or increasing the pore-filling of TiO₂ inside mesoporous NiO could be a reasonable strategy to significantly improve the efficiency of such solar cells.

As mentioned above, the length of PB6 dye is *ca.* 2.5 nm, which provides us an opportunity to study the effect of the thickness of Al₂O₃ on the performance of the solar cells. In principle, a too thin Al₂O₃ layer cannot effectively suppress charge recombination loss and render unsatisfactory performance. Conversely, a too thick Al₂O₃ layer could completely bury the dye and the TiO₂ cannot sufficiently contact with the acceptor of the dye, which will induce unsatisfactory performance as well due to low regeneration efficiencies. There should be an optimal thickness of Al₂O₃ giving an optimized performance. Different thicknesses of Al₂O₃ (0.08, 0.5, 1, 2 and 10 nm) were therefore investigated in NiO-PB6-Al₂O₃-TiO₂ solar cells. From Fig. 5, *ca.* 1 nm of Al₂O₃ was proven to be the optimal thickness, because it only covers the entire electron donating unit, triphenylamine (TPA) of PB6, and allows the whole electron acceptor part (perylene monoimide (PMI)) buried inside TiO₂, which is expected to be the optimal configuration for charge separation between dye and semiconductors.

With the Al₂O₃ layer thinner than 1 nm, less photocurrent and photovoltage was observed, implying more extensive recombination in these devices. With 2 nm Al₂O₃ film, the photocurrent from the corresponding device also significantly decreased, suggesting that the charge separation probably is inefficient. The hypothesis can be further supported from the results utilizing a 10 nm Al₂O₃ layer, resulting in solar cells without any obvious photocurrent likely to be caused by the absence of contact between dye and TiO₂.

In summary, solid state p-type dye-sensitized NiO-dye-TiO₂ core-shell solar cells have been proposed and fabricated for the first time, in which the NiO is sensitized by the organic PB6 dye, after which a TiO₂ layer is deposited by ALD to form the dye sensitized NiO-dye-TiO₂ core-shell structure. By inserting a thin insulating Al₂O₃ layer, the charge recombination between NiO and TiO₂ after charge injection from dye was significantly retarded. On the basis of the molecular extension of dye, the effect of Al₂O₃ layer thickness on the solar cell performance was further investigated, showing an optimal thickness of *ca.* 1 nm for the PB6-based devices. The optimal Al₂O₃ thickness should be different from different dyes, which encourages us to apply the strategy on other dye systems in future study. Furthermore, other n-type metal oxides can be considered as electron transport materials instead of TiO₂ in the core-shell solar cells. This type of solar cell holds the potential to rival conventional liquid p-type dye sensitized solar cells after systematic studies and



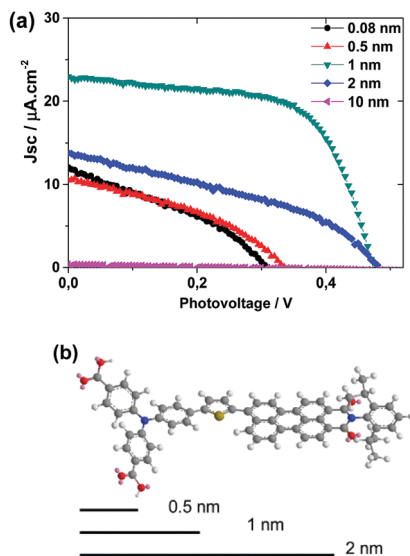


Fig. 5 (a) J - V curves for NiO-PB6-Al₂O₃-TiO₂ solar cells with different Al₂O₃ thickness layers; (b) the 3-D molecular structure of PB6 with 0.5 nm, 1 nm and 2 nm length scales as comparison.

optimization of different components, and may show potential for application in solar fuel devices as well.

The authors are grateful for the financial support from the Swedish Energy Agency (grant 43599-1). Lei Tian also thanks the China Scholarship Council (CSC) for scholarship support.

Conflicts of interest

The authors declare no competing financial interests.

Notes and references

- B. O'regan and M. Grätzel, *Nature*, 1991, **353**, 737.
- J. He, H. Lindström, A. Hagfeldt and S.-E. Lindquist, *J. Phys. Chem. B*, 1999, **103**, 8940.
- V. Nikolaou, A. Charisiadis, G. Charalambidis, A. G. Coutsolelos and F. Odobel, *J. Mater. Chem. A*, 2017, **5**, 21077.
- A. Nattestad, A. J. Mozer, M. K. Fischer, Y.-B. Cheng, A. Mishra, P. Bäuerle and U. Bach, *Nat. Mater.*, 2010, **9**, 31.

- K. A. Click, B. M. Schockman, J. T. Dilenschneider, W. D. McCulloch, B. R. Garrett, Y. Yu, M. He, A. E. Curtze and Y. Wu, *J. Phys. Chem. C*, 2017, **121**, 8787.
- E. A. Gibson, A. L. Smeigh, L. Le Pleux, J. Fortage, G. Boschloo, E. Blart, Y. Pellegrin, F. Odobel, A. Hagfeldt and L. Hammarström, *Angew. Chem., Int. Ed.*, 2009, **121**, 4466.
- P. B. Pati, L. Zhang, B. Philippe, R. Fernández-Terán, S. Ahmadi, L. Tian, H. Rensmo, L. Hammarström and H. Tian, *ChemSusChem*, 2017, **10**, 2480.
- F. Li, K. Fan, B. Xu, E. Gabrielsson, Q. Daniel, L. Li and L. Sun, *J. Am. Chem. Soc.*, 2015, **137**, 9153.
- E. A. Gibson, *Chem. Soc. Rev.*, 2017, **46**, 6194.
- L. Zhang, G. Boschloo, L. Hammarström and H. Tian, *Phys. Chem. Chem. Phys.*, 2016, **18**, 5080.
- H. Tian, B. Xu, H. Chen, E. M. Johansson and G. Boschloo, *ChemSusChem*, 2014, **7**, 2150.
- T. T. T. Pham, S. K. Saha, D. Provost, Y. Farré, M. Raissi, Y. Pellegrin, E. Blart, S. Vedraïne, B. Ratier, D. Aldakov, F. Odobel and J. Bouclé, *J. Phys. Chem. C*, 2017, **121**, 129.
- N. J. Cherepy, G. P. Smestad, M. Grätzel and J. Z. Zhang, *J. Phys. Chem. B*, 1997, **101**, 9342.
- Y. Tachibana, J. E. Moser, M. Grätzel, D. R. Klug and J. R. Durrant, *J. Phys. Chem.*, 1996, **100**, 20056.
- F. Cao, G. Oskam, G. J. Meyer and P. C. Searson, *J. Phys. Chem.*, 1996, **100**, 17021.
- Y.-M. Lee, C.-H. Hsu and H.-W. Chen, *Appl. Surf. Sci.*, 2009, **255**, 4658.
- Y.-M. Lee and C.-H. Lai, *Solid-State Electron.*, 2009, **53**, 1116.
- K. H. Wong, K. Ananthanarayanan, S. R. Gajjala and P. Balaya, *Mater. Chem. Phys.*, 2011, **125**, 553.
- L. Tian, J. Föhlinger, P. B. Pati, Z. Zhang, J. Lin, W. Yang, M. Johansson, T. Kubart, J. Sun, G. Boschloo, L. Hammarström and H. Tian, *Phys. Chem. Chem. Phys.*, 2018, **20**, 36.
- L. D'Amario, L. J. Antila, B. Pettersson Rimgard, G. Boschloo and L. Hammarström, *J. Phys. Chem. Lett.*, 2015, **6**, 779.
- Z. Bian, T. Tachikawa, S.-C. Cui, M. Fujitsuka and T. Majima, *Chem. Sci.*, 2012, **3**, 370.
- R. J. Lindquist, B. T. Phelan, A. Reynal, E. A. Margulies, L. E. Shoer, J. R. Durrant and M. R. Wasielewski, *J. Mater. Chem. A*, 2016, **4**, 2880.
- C. Prasittichai and J. T. Hupp, *J. Phys. Chem. Lett.*, 2010, **1**, 1611.
- G. Natu, Z. Huang, Z. Ji and Y. Wu, *Langmuir*, 2011, **28**, 950.
- N. P. Kobayashi, C. L. Donley, S.-Y. Wang and R. S. Williams, *J. Cryst. Growth*, 2007, **299**, 218.
- H. Tian, J. Oscarsson, E. Gabrielsson, S. K. Eriksson, R. Lindblad, B. Xu, Y. Hao, G. Boschloo, E. M. Johansson and J. M. Gardner, *Sci. Rep.*, 2014, **4**, 4282.
- M. Quintana, T. Edvinsson, A. Hagfeldt and G. Boschloo, *J. Phys. Chem. C*, 2007, **111**, 1035.
- H. Zhu, A. Hagfeldt and G. Boschloo, *J. Phys. Chem. C*, 2007, **111**, 17455.
- L. Li, E. A. Gibson, P. Qin, G. Boschloo, M. Gorlov, A. Hagfeldt and L. Sun, *Adv. Mater.*, 2010, **22**, 1759.

