

新型稠环电子受体的界面修饰对钙钛矿太阳能电池性能的影响

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摘要 钙钛矿太阳能电池(perovskite solar cells, PSCs)因具有能量转换效率(power conversion efficiency, PCE)高、成本低、易于大面积制造等优点而被科学家们广泛关注。氧化物电子传输层的合理界面设计及修饰对提高器件的PCE和工作长期稳定性有着十分重要的意义。因此,本文采用一种含有烷基噻吩基侧链的稠环电子受体材料3,9-二(2-亚甲基-(3-(1,1-二氟甲烯基)-茚酮))-5,5,11,11-四(5-己基噻吩)-二噻吩并[2,3-d:2',3'-d']-s-引达省[1,2-b:5,6-b']二噻吩(3,9-bis(2-methylene-(3-(1,1-dicyanomethylene)-indanone))-5,5,11,11-tetrakis(5-hexylthienyl)-dithieno[2,3-d:2',3'-d']-s-indaceno[1,2-b:5,6-b']dithiophene, ITIC-Th)修饰TiO₂电子传输层,制备高效稳定的平面结PSCs。研究结果显示,ITIC-Th的界面修饰改善了TiO₂薄膜的形貌、接触角等性质,促进了钙钛矿晶粒的高质量生长,大幅度减少了器件表界面的电荷复合,明显提升了光生载流子的抽取率和输运效率,使经ITIC-Th界面修饰的PSC的PCE从未经界面修饰的15.43%显著提高到18.91%。与此同时,器件稳定性的研究结果显示,在室温和湿度为30%的条件下,经ITIC-Th界面修饰的PSC的PCE在放置约1000 h后依然保持原来的90%,明显高于未经界面修饰的PSC。研究结果对PSC光伏性能的提升具有重要的实际应用价值和学术意义。

关键词 稠环电子受体, ITIC-Th, 钙钛矿太阳能电池, 界面修饰

有机-无机钙钛矿材料由于具有易调节的带隙、高载流子迁移率和明显的缺陷耐受性等特点而成为新型太阳能电池光吸收材料的理想选择之一^[1]。当前,钙钛矿太阳能电池(perovskite solar cells, PSCs)的能量转换效率(power conversion efficiency, PCE)从2009年Miyasaka等人首次报道的3.8%迅速提升至23.7%^[2-5],超过了商业化的铜铟镓硒和碲化镉太阳能电池,普遍被认为是最具有发展前景的薄膜太阳能电池之一。

PSCs的器件结构通常由导电玻璃基底、电子传输

层(electronic transport layer, ETL)、钙钛矿光吸收层、空穴传输层和金属背电极组成^[6]。其中,ETL的主要功能是传输电子并阻挡空穴传输,促进平衡电荷输运和减少电荷复合,对PSCs的PCE和寿命等性能至关重要^[7,8]。传统的电子传输材料主要有TiO₂, SnO₂, ZnO和富勒烯及其衍生物等^[9]。锐钛矿型的TiO₂由于具有优异的光学透射率、半导体特性和化学稳定性,常被用作正置结构PSCs中的ETL^[3,10-12]。然而,其粗糙的表面和大量的表面缺陷容易导致钙钛矿薄膜结晶不佳和过大

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的电流密度-电压(*J-V*)曲线滞后^[13,14]。例如, PSCs的光伏性能有时取决于测试扫描的方向和速度, 这使得其准确的PCE测定面临着挑战^[15]。大量的研究结果表明, 通过对TiO₂薄膜的表面改性, 可以促进电子提取和钝化陷阱状态^[16,17]。例如, 富勒烯及其衍生物^[18]作为ETL的修饰层被引入n-i-p PSCs中, 增加了光活性层与ETL之间的接触, 提高了光生电荷的抽取率和输运效率, 从而使器件的PCE达到了19%以上^[19,20]。最近, 几种非富勒烯稠环电子受体材料(fused-ring electron acceptor, FREAs)也被用作ETL的修饰层, 不仅使其器件的PCE提高到20%以上, 同时还大幅度提高了PSCs的工作长期稳定性^[18,21]。虽然非富勒烯FREAs最初是作为电子受体广泛应用于有机太阳能电池中^[22~24], 但是由于其结构是基于带有强吸电子基团的电子给体延伸稠环^[18,22~24], 相比较于传统的富勒烯及其衍生物, 具有可调的光学带隙和能级结构、良好的电子传输能力、优异的光热稳定性等优异特性^[22]。因此, FREAs作为ETL修饰层的应用是目前普遍被认为能够进一步有效提高PSCs性能的技术途径之一。

本文中, 我们利用一种新型的稠环电子受体ITIC-Th^[22,25]修饰TiO₂电子传输层, 采用器件结构ITO/TiO₂/ITIC-Th/(FAPbI₃)_x(MAPbCl₃)_{1-x}/Spiro-OMeTAD/Ag制备n-i-p平面结PSCs, 并结合扫描电子显微镜、稳态荧光光谱和电化学阻抗谱等测试技术对PSC界面的结构、形貌和光电性质等进行表征与分析, 器件结构和ITIC-Th的分子结构分别如图1(a)和(b)所示。研究结果显示, 经ITIC-Th界面修饰的PSC的PCE从未经界面修饰的15.43%显著提高到18.91%。并且, 在室温和湿度为30%的条件下放置约1000 h后其PCE依然保持原来的90%。

1 实验

(i) 原料。碘化铅(II)(PbI₂)(99.999%)购自Alfa-Aesar。异丙醇钛(IV)(TTIP)(97%)、乙酸甲脒盐(99%)、氢碘酸(HI)(57wt%)、无水二甲基甲酰胺

(DMF)(99.8%)、甲胺盐酸盐(MACl)、无水二甲基亚砜(DMSO)(99.9%)、乙腈(99.8%)、氯苯(99.8%)、4-叔丁基吡啶(4-tBP)(96%)和双三氟甲烷磺酰亚胺锂盐(LiTFSI)(99.95%)购自Sigma-Aldrich。ITIC-Th和Spiro-OMeTAD购自Ossila。双三氟甲基磺酰亚胺酰(FK209)购自Dylenanmo。其中, 甲脒碘(FAI)是用乙酸甲脒盐和氢碘酸依据文献[26]合成的, TiO₂纳米颗粒是根据文献[27]报道的异丙醇钛水解方法制备的, PbI₂(DMSO)络合物是用PbI₂和DMSO按照文献[28]制备的。所有材料在使用前均未被进一步提纯。

(ii) 器件制备。首先, ITO玻璃基底依次使用洗涤剂、去离子水、丙酮和异丙醇各超声清洗15 min, 吹干后经紫外臭氧清洗10 min; 随后, 20 mg mL⁻¹的TiO₂纳米颗粒溶液在ITO基板上以4000 r min⁻¹转速旋涂50 s, 可重复旋涂工艺数次获得所需厚度的TiO₂薄膜, 然后将TiO₂薄膜在大气环境下120℃退火60 min; 在氩气气氛保护的手套箱内, 将1 mg mL⁻¹的ITIC-Th氯苯溶液在涂覆TiO₂薄膜表面以2000 r min⁻¹转速旋涂50 s, 随后120℃热台退火20 min。对于钙钛矿层, 将DMF中的1.5 mol L⁻¹ PbI₂(DMSO)前驱体溶液在70℃下预热, 并在ITIC-Th修饰层表面以2000 r min⁻¹转速旋涂45 s; 随后将70 mg mL⁻¹的FAI和MACl的混合异丙醇溶液在PbI₂(DMSO)薄膜表面以2000 r min⁻¹转速旋涂40 s, 并120℃热台退火2 h。自然冷却至室温后, Spiro-OMeTAD溶液以2000 r min⁻¹转速旋涂50 s, 沉积在钙钛矿层顶部。其中, Spiro-OMeTAD溶解在氯苯(60 mmol L⁻¹)中, 并加入30 mmol L⁻¹ Li-TFSI(520 mg mL⁻¹的乙腈溶液), 200 mmol L⁻¹ 4-tBP和1.8 mmol L⁻¹ FK209(300 mg mL⁻¹)。最后, 利用高真空热蒸发镀膜机在约10⁻⁴ Pa的真空条件下蒸镀100 nm金属银电极, 其中电池的有效面积为0.1 cm²。同时, 在相同条件下制备没有ITIC-Th修饰层的对照电池样品。

(iii) 表征方法。光电流密度-电压(*J-V*)性能测试是在光强为100 mW cm⁻²的AM 1.5G的模拟太阳光下通

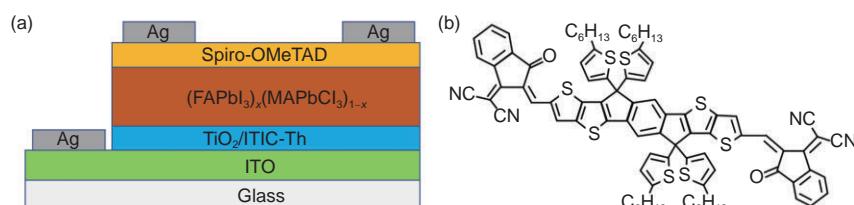


图1 (网络版彩色)器件结构(a)和ITIC-Th分子结构(b)

Figure 1 (Color online) Device structure (a) and molecular structure of ITIC-Th (b)

过Keithley 2420测试系统进行测量的。入射光子-电子转化效率(incident photon-electron conversion efficiency, IPCE)使用Newport太阳能电池光谱响应测量系统进行测量。采用场发射扫描电子显微镜(scanning electron microscope, SEM, SUPRA 55)对钙钛矿太阳能电池的微观形貌进行表征。采用紫外可见光光谱仪(UV-Vis, UV-2600)和稳态瞬态近红外荧光光谱仪(photoluminescence, PL, FLS 980)对钙钛矿太阳能电池的光学性质进行表征。采用接触角测量仪(SDC-100)对ITIC-Th修饰TiO₂薄膜前后的接触角进行测试。交流阻抗谱是通过VersaSTAT3化学工作站(Princeton Applied Research)进行测试。

2 结果与讨论

图2(a)和(b)分别为TiO₂薄膜和TiO₂/ITIC-Th薄膜的SEM表面形貌图。对比发现,经ITIC-Th修饰的TiO₂薄膜

更加致密和光滑平整。结果表明,ITIC-Th修饰层可以减少TiO₂薄膜的表面缺陷,提高ETL膜层质量,增加与钙钛矿的接触等,从而有利于减少光生电荷的界面复合^[29]。此外,图2(c)和(d)分别为TiO₂基和TiO₂/ITIC-Th基PSCs的SEM截面形貌图。对比发现,虽然TiO₂基和TiO₂/ITIC-Th基的钙钛矿吸光层具有同样厚度,但是TiO₂/ITIC-Th基的钙钛矿晶粒尺寸(约800 nm)明显比TiO₂基的钙钛矿晶粒尺寸(约400 nm)大,并且TiO₂/ITIC-Th基钙钛矿晶粒在纵向方向上几乎贯穿整个钙钛矿吸光层,而TiO₂基钙钛矿吸光层却包含大量的晶界。结果表明,经ITIC-Th修饰的TiO₂有利于促进钙钛矿晶粒长大。根据文献报道,钙钛矿晶粒的质量将影响电荷传输和载流子复合,所以晶粒的大小对短路电流密度(short-circuit current density, J_{sc})至关重要^[30],晶界处众多的电荷陷阱对界面复合和非辐射复合有重要影响,紧凑无针孔的钙钛矿薄膜可以提高钙钛矿太阳能

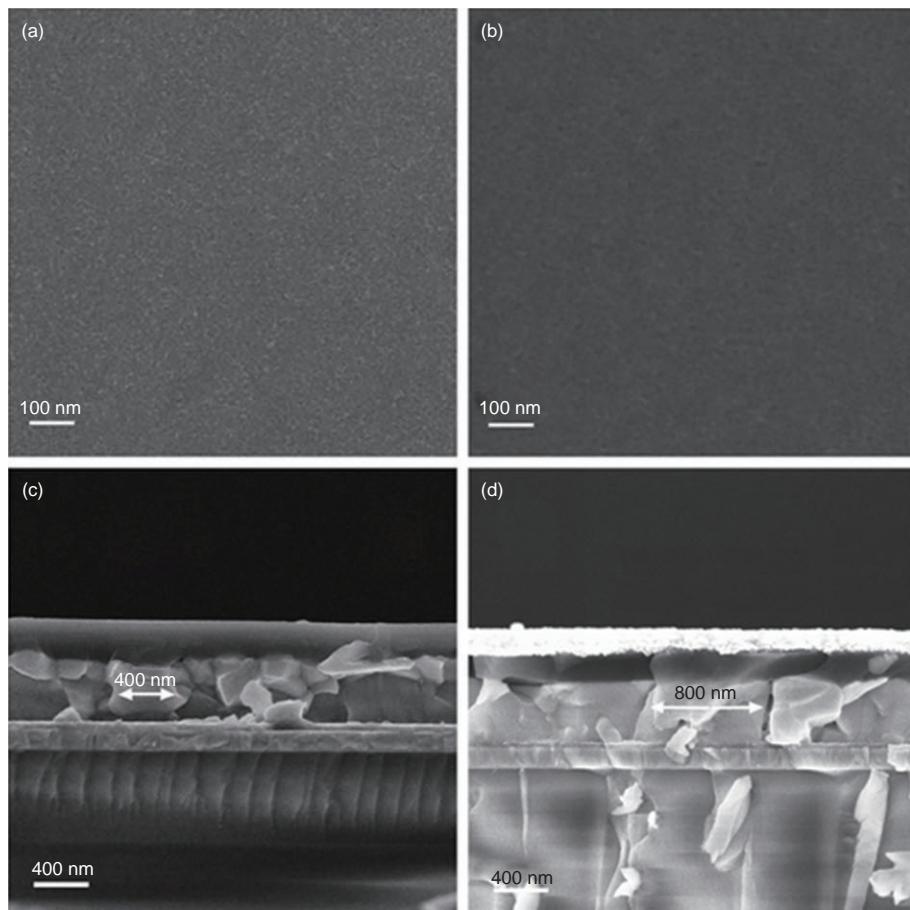


图 2 SEM形貌图. (a) TiO₂薄膜表面; (b) TiO₂/ITIC-Th薄膜表面; (c) ITO/TiO₂基PSCs横截面; (d) ITO/TiO₂/ITIC-Th基PSCs横截面
Figure 2 SEM images. Top-view of TiO₂ film (a) and TiO₂/ITIC-Th film (b); cross-sectional images of TiO₂-based PSCs (c) and TiO₂/ITIC-Th-based PSCs (d)

电池的开路电压(open-circuit voltage, V_{oc})和 J_{sc} ^[31].

为了探究ETL的表面浸润性与钙钛矿晶体生长的相关性, 分别使用水和DMF对 TiO_2 薄膜和 $\text{TiO}_2/\text{ITIC-Th}$ 薄膜进行接触角测试。从图3可以看出, 经ITIC-Th修饰后的 TiO_2 薄膜, 水滴的接触角从41°增加到55°, DMF滴的接触角从16°增加到30°。结果表明, ITIC-Th修饰可有效降低 TiO_2 薄膜的亲水性。基于之前钙钛矿晶粒生长与ETL表面浸润性的相关性的文献[30]报道, ETL薄膜的疏水性增加可以抑制钙钛矿晶粒的非均匀成核, 从而促进其晶界迁移, 促进大晶粒生长。图2(d)和图3的实验结果与文献[32]报道的实验结果相一致。

图4(a)为ITO基底、 ITO/TiO_2 基底和 $\text{ITO}/\text{TiO}_2/\text{ITIC-Th}$ 基底的UV-Vis透过光谱。可以看出, 除了450~550 nm波长, ITO/TiO₂基底和ITO/TiO₂/ITIC-Th基底的光透过率都比ITO基底的低; 并且, 在550~750 nm

区间, ITO/TiO₂/ITIC-Th基底的光透过率也略低于ITO/TiO₂基底。分析其原因, 可能是由ITIC-Th在该区间产生的额外光吸收导致的^[24]。分别在以上3种基底上旋涂(FAPbI_3)_x(MAPbCl_3)_{1-x}钙钛矿薄膜, 并对它们进行稳态荧光光谱测试, 实验结果如图4(b)所示。可以看出, 基于ITO/TiO₂/ITIC-Th基的钙钛矿薄膜拥有最低荧光强度, 表明ITIC-Th修饰进一步增强了ETL对载流子的抽取率和运输效率^[29], 从而有利于提高PSCs的PCE。

图5(a)和表1分别是基于ITO/TiO₂基和ITO/TiO₂/ITIC-Th基的PSCs的J-V曲线图和光伏参数数据。可以看出, ITO/TiO₂/ITIC-Th基PSC的 V_{oc} 、 J_{sc} 、填充因子(fill factor, FF)和PCE分别为1.05 V, 23.56 mA cm⁻², 76.58%和18.91%, 明显高于ITO/TiO₂基PSC的光伏性能(V_{oc} 为1.02 V, J_{sc} 为22.89 mA cm⁻², FF为66.10%, PCE为15.43%); 其次, ITO/TiO₂/ITIC-Th基PSC的正反扫的

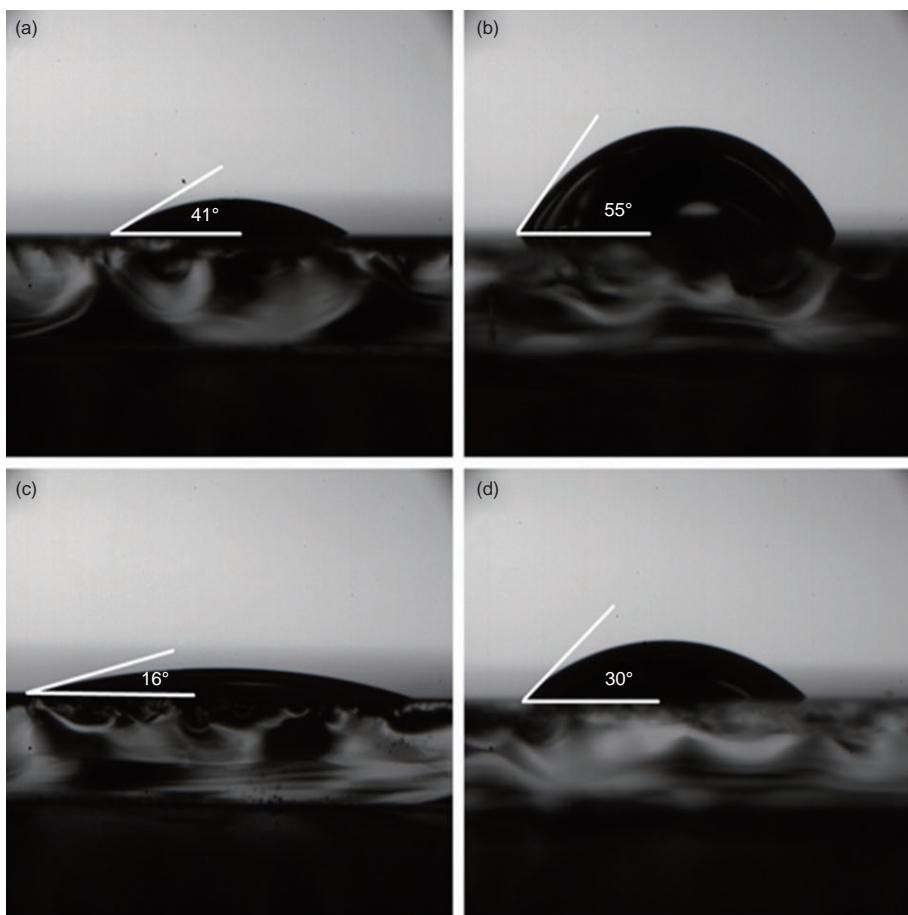


图3 接触角图像. (a) TiO_2 薄膜的水滴接触角; (b) $\text{TiO}_2/\text{ITIC-Th}$ 薄膜的水滴接触角; (c) TiO_2 薄膜的DMF液滴接触角; (d) $\text{TiO}_2/\text{ITIC-Th}$ 薄膜的DMF液滴接触角

Figure 3 Contact angle images. Images of water contact angles of TiO_2 film (a) and $\text{TiO}_2/\text{ITIC-Th}$ film (b); images of contact angles of DMF droplet on TiO_2 film (c) and $\text{TiO}_2/\text{ITIC-Th}$ film (d)

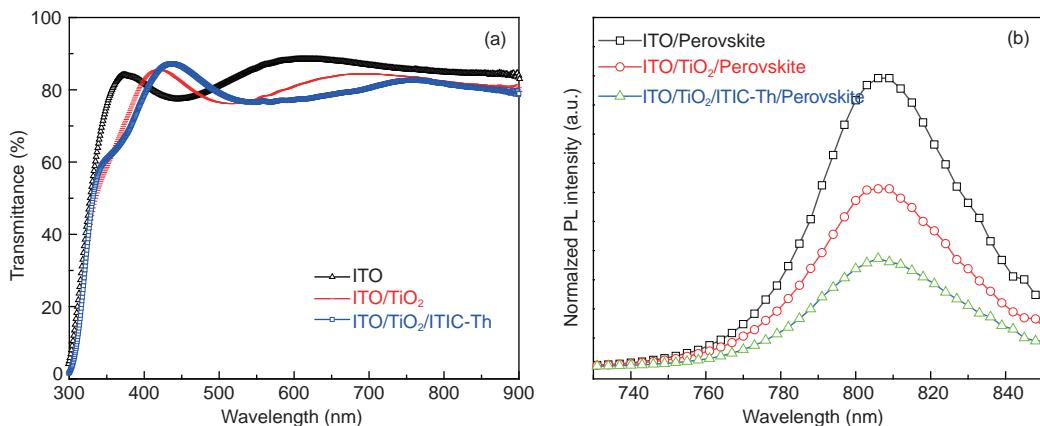


图4 (网络版彩色)UV-Vis透过光谱图和稳态PL光谱图. (a) ITO, ITO/TiO₂和ITO/TiO₂/ITIC-Th的UV-Vis透过光谱图; (b) ITO钙钛矿薄膜, ITO/TiO₂钙钛矿薄膜和ITO/TiO₂/ITIC-Th钙钛矿薄膜的稳态PL光谱图

Figure 4 (Color online) UV-Vis transmittance spectra and steady-state PL spectra. (a) UV-Vis transmittance spectra of ITO, ITO/TiO₂ and ITO/TiO₂/ITIC-Th; (b) steady-state PL spectra of perovskite films on ITO, ITO/TiO₂ and ITO/TiO₂/ITIC-Th

PCE差别仅为4.4%，也明显低于ITO/TiO₂基PSC的10.4%。同时，性能的提升也通过统计50个相同器件工艺的ITO/TiO₂基和ITO/TiO₂/ITIC-Th基的PSCs的光伏参数数据得到了进一步证实(图5(b))。一方面，相比较于TiO₂，ITIC-Th的最低未占有轨道能级(lower unoccupied molecular orbit, LUMO)与(FAPbI₃)_x(MAPbCl₃)_{1-x}钙钛矿吸光层的LUMO差别更小^[29]，更有利电子的抽取与分离，促进Voc和FF的提升；另一方面，ITIC-Th修饰不仅修复了TiO₂薄膜的表面缺陷，还促进了大晶粒的钙钛矿长大，从而大幅度减少了光生载流子的界面复合，有效地提高了J_{sc}和FF。与此同时，还测量了PSCs的外量子效率(external quantum efficiency, EQE)，结果如图5(c)所示。可以看出，在400~800 nm的波长范围内，ITO/TiO₂/ITIC-Th基的PSCs比ITO/TiO₂基具有更高的光电子转换效率。基于它们的EQE光谱曲线计算出的积分电流密度分别为21.92和22.84 mA cm⁻²，这与J-V曲线的J_{sc}结果基本一致。此外，为了进一步深入研究ITIC-Th修饰对PSCs的电荷迁移动力学的影响，在暗条件下对ITO/TiO₂基和ITO/TiO₂/ITIC-Th基的PSCs施加0.2 V直流偏压和20 mA的电流，在0.1 Hz~1 MHz范围内测量的EIS谱结果如图5(d)所示。可以看出，相比较于ITO/TiO₂基的EIS曲线，ITO/TiO₂/ITIC-Th基的EIS曲线的高频半圆弧变小了将近1/3，而低频半圆弧变大了将近1倍。根据奈奎斯特图谱的高频半圆弧源于电荷迁移动力学，低频半圆弧源于电荷复合动力学^[33]，表明界面处电荷的输运增加，复合损失减小，进一步证实了ITIC-Th修饰TiO₂薄膜可以有效地提高PSCs的PCE。图5

(e)显示了ITO/TiO₂/ITIC-Th基PSC在不同反向扫速条件下测试的J-V曲线。可以看出，反扫曲线之间只有细微的差别，表明其PCE具有良好的稳定性。此外，为了进一步验证ITO/TiO₂/ITIC-Th基PSC的PCE的输出稳定性和光响应特性，采用在最大功率点跟踪(maximum power point tracking, MPPT)测试条件下，即在偏压为0.87 V，光强为100 mW cm⁻²的AM 1.5G的模拟太阳光下，500 s间断光照射，测量电池的电流密度输出值，结果如图5(f)所示。可以看出，在每次接受光照后，电流都迅速达到高值并快速趋于平稳；在500 s后，ITO/TiO₂/ITIC-Th基PSC的电流密度输出值几乎与测试开始时相当，约为21.10 mA cm⁻²；其相应的PCE也稳定在18.36%，与其在表1中的PCE值偏差仅约2.9%，表明其具有良好的功率输出稳定性。

最后，为了研究ITIC-Th修饰TiO₂薄膜对于PSCs稳定性的影响，未经过任何封装的ITO/TiO₂基和ITO/TiO₂/ITIC-Th基的PSCs在室温和湿度30%的条件下，在42 d(约1000 h)内对电池器件进行间断性光伏性能测试，实验结果如图6所示。可以看出，ITO/TiO₂/ITIC-Th基PSCs的PCE在42 d后仍然保持原来的90%以上，而未修饰ITIC-Th的PSCs的PCE已衰减至原来的65%。实验结果表明，ITIC-Th修饰可以修复TiO₂薄膜的界面缺陷，并改变其表面疏水性，促进钙钛矿晶粒长大，减少钙钛矿/ETL界面的电荷复合，有效提高钙钛矿/ETL界面的电荷抽取率和输运效率，从而提高电池器件的工作长期稳定性。研究结果对PSCs性能的提升和加快商业化应用有着重要的实际价值。

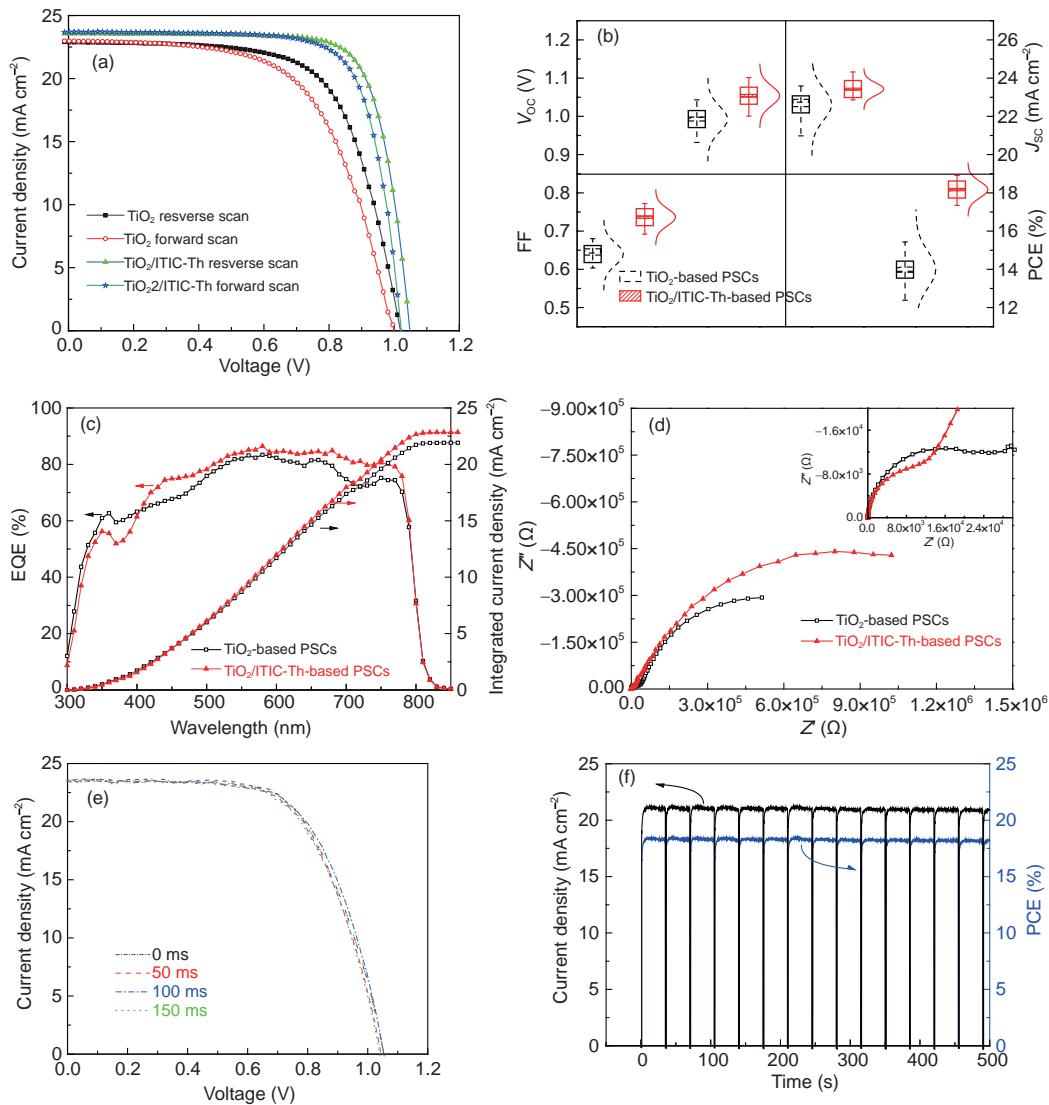


图5 (网络版彩色)器件光伏性能. (a) 基于 TiO_2 和 $\text{TiO}_2/\text{ITIC-Th}$ 的PSCs正向/反向扫描J-V曲线; (b) 基于 TiO_2 和 $\text{TiO}_2/\text{ITIC-Th}$ 反向扫描J-V的光伏参数统计偏差; (c) 基于 TiO_2 和 $\text{TiO}_2/\text{ITIC-Th}$ 的PSCs的EQE和积分电流图谱; (d) 在0.2 V偏压下, 于黑暗条件下测得基于 TiO_2 和 $\text{TiO}_2/\text{ITIC-Th}$ 的PSCs的奈奎斯特图, 插图为高频放大图谱; (e) 基于 $\text{TiO}_2/\text{ITIC-Th}$ 的PSCs反向扫描不同扫速的J-V曲线; (f) 0.87 V偏压下, 基于 $\text{TiO}_2/\text{ITIC-Th}$ 的PSCs的光响应、稳定输出的PCEs和 J_{sc}

Figure 5 (Color online) Photovoltaic performance. (a) J - V curves of the champion PSCs with TiO_2 or $\text{TiO}_2/\text{ITIC-Th}$ by forward and reverse scan; (b) statistical deviation of the photovoltaic parameters of 50 PSCs with TiO_2 or $\text{TiO}_2/\text{ITIC-Th}$ by reverse scan; (c) EQE plots and the integrated current density of PSCs with TiO_2 and TiO_2/ITIC as ETLs; (d) Nyquist plots of TiO_2 and $\text{TiO}_2/\text{ITIC-Th}$ based PSCs in the dark at 0.2 V bias with inset showing a magnification of the high-frequency region; (e) J - V curves of PSC with $\text{TiO}_2/\text{ITIC-Th}$ under different scanning rates by reverse scan; (f) light response and stabilized PCE and photocurrent density of PSCs with $\text{TiO}_2/\text{ITIC-Th}$ measured at 0.87 V bias

表1 基于不同ETLs的PSCs主要光伏参数

Table 1 Photovoltaic parameters of PSCs based on different ETLs

ETL	Scan direction	V_{oc} (V)	J_{sc} (mA cm^{-2})	FF (%)	PCE (%)
TiO_2	R(champion)	1.02	22.89	66.10	15.43
	F(champion)	0.99	22.98	60.38	13.83
$\text{TiO}_2/\text{ITIC-Th}$	R(champion)	1.05	23.56	76.58	18.91
	F(champion)	1.03	23.68	74.72	18.08

3 结论

本文利用非富勒烯受体材料ITIC-Th作为TiO₂电子传输层的界面修饰层，实现了PSCs的PCE从未界面修饰的15.43%显著提升到18.91%，并且明显降低了J-V曲线的迟滞现象。研究结果表明，ITIC-Th的界面修饰改善了TiO₂薄膜的形貌，促进了钙钛矿晶粒的高质量生长，大幅度减少了表界面的电荷复合，明显提高了光生载流子的抽取率和输运效率。其次，器件稳定性的研究结果显示，未封装的TiO₂/ITIC-Th基PSC不仅在MPPT连续光照500 s的条件下保持输出功率不变，而且在室温和湿度30%的条件下放置约1000 h后其PCE依然保持原来的90%，明显高于纯TiO₂基PSC。因此，ITIC-Th修饰TiO₂电子传输层是制备高效稳定的PSCs的一种有效的界面优化设计方法。

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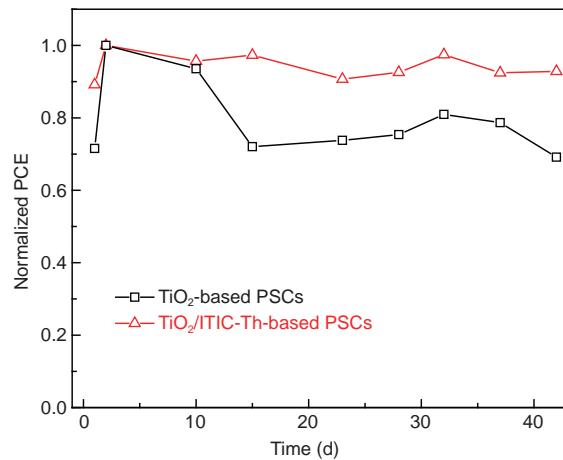


图 6 (网络版彩色)基于TiO₂和TiO₂/ITIC-Th ETLs的未封装PSCs的PCE归一化衰减情况

Figure 6 (Color online) Normalized PCE attenuation of unpackaged PSCs based on TiO₂ and TiO₂/ITIC-Th

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Summary for “新型稠环电子受体的界面修饰对钙钛矿太阳能电池性能的影响”

Interfacial modification for perovskite solar cells using a novel fused-ring electron acceptor

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Perovskite solar cells have recently attracted significant attention as the promising candidate of commercial photovoltaic devices with high power conversion efficiency, low cost and large-scale processing.

Anatase-type TiO₂ is often used as an electronic transport layer in a state-of-the-art perovskite solar cells due to its excellent optical transmittance, semiconductor characteristics, and chemical stability. However, its rough surface with a large number of surface defects leads to poor crystallization of the perovskite film and serious hysteresis effect. Recent studies have shown that suitable interfacial modification plays an important role in enhancing power conversion efficiency and long-term stability of the perovskite solar cells. Several fused-ring electron acceptors have been introduced into n-i-p perovskite solar cells as the interfacial modifications for the electronic transport layer, which dramatically improve the performance and the long-term stability of the devices. The fused-ring electron acceptors are widely used as the electron acceptors in organic solar cells, and their structures are based on an electron donating fused ring with strong electron withdrawing groups, which contributes to adjustable optical band gap and energy level structure, good electronic transfer capability, excellent thermal and photochemical stability.

Therefore, a facile interface engineering method for all-solution-processed perovskite solar cells is reported in this paper. The fused-ring electron acceptor ITIC-Th containing alkylthiophene side chains is applied to modify TiO₂ electronic transport layer to prepare the planar perovskite solar cells with excellent performance and stability. The main results and discussions are summarized as follows:

(1) The ITIC-Th modified TiO₂ film is much denser and smoother than the original TiO₂ film. The images of scanning electron microscope show that the interfacial modification using ITIC-Th improves the morphology and increases the water contact angle of the electronic transport layer, which effectively enhances the quality and grain size of the perovskite crystals.

(2) The characterizations of the electronic transport layer by UV-Vis transmission and photoluminescence spectroscopy indicate that ITIC-Th produces additional light absorption in the wavelength interval from 550 to 750 nm, so the transmittance of the modified electronic transport layer is slightly lower than that of ITO/TiO₂ substrate; however, ITIC-Th has a strong fluorescence quenching effect, resulting in beneficial properties on the extraction, transportation and collection of photo-generated carriers for the modified electronic transport layer, which greatly reduces the surface recombination of charge carriers.

(3) Planar solar cells with the structure of ITO/electronic transport layer/(FAPbI₃)_x(MAPbCl₃)_{1-x}/spiro-OMeTAD/Ag are successfully prepared. Consequently, the champion power conversion efficiency of the perovskite solar cells increases from 15.43% to 18.91% after the introduction of ITIC-Th. Moreover, the stability of the perovskite solar cells without encapsulation is investigated. As a result, the TiO₂/ITIC-Th based device exhibits excellent stability with only 10% degradation after 1000 h in ambient humidity of 30% at room temperature, which is superior to that of the TiO₂ based device. This work provides an important candidate in practical application for improving the performance of perovskite solar cells.

fused ring electron acceptor, ITIC-Th, perovskite solar cells, interfacial modification

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