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Nanocrystals as performance-boosting materials for solar cells

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Nanocrystals (NCs) have been widely studied owing to their distinctive properties and promising application in new-generation photoelectric devices. In photovoltaic devices, semiconductor NCs can act as efficient light harvesters for high-performance solar cells. Besides light absorption, NCs have shown great significance as functional layers for charge (hole and electron) transport and interface modification to improve the power conversion efficiency and stability of solar cells. NC-based functional layers can boost hole/electron transport ability, adjust energy level alignment between a light absorbing layer and charge transport layer, broaden the absorption range of an active layer, enhance intrinsic stability, and reduce fabrication cost. In this review, recent advances in NCs as a hole transport layer, electron transport layer, and interfacial layer are discussed. Additionally, NC additives to improve the performance of solar cells are demonstrated. Finally, a summary and future prospects of NC-based functional materials in solar cells are presented, addressing their limitations and suggesting potential solutions.

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1. Introduction

Nanocrystals (NCs), sometimes termed as quantum dots (QDs) or nanoparticles (NPs), with a size less than 100 nm, are popular worldwide and have been paid extensive attention owing to their outstanding photoelectric properties. In the energy field, photovoltaic devices based on semiconductor NCs are among the most potential systems with high power conversion efficiency (PCE), good stability, low cost, facile fabrication, and other advantages.^{1–16} In recent years, NCs have been widely used as light harvesting layers in high-performance solar cells. Semiconducting NCs such as PbX (X = S, Se, and Te), CdSe, and CuInS₂ have been suggested as excellent light harvesters in third-generation solar cells.^{11,14,15,17–22} Additionally, perovskite NCs are also good alternatives for light harvesting in solar cells.^{12–14,16,23–28} Besides active layers (light harvesting layers), functional layers based on NCs, mainly including hole transport layers (HTLs),^{29–99} electron transport layers (ETLs)^{100–173} and interfacial functional layers (IFLs),^{174–221} are of great importance in solar cells. Notably, NC additives also boost the performance of solar cells through defect passivation, plasmonic effect, solar concentration, light up-conversion and down-conversion/shifting, light scattering and reflection, and heat sinks.^{222–258}

To efficiently transport charge in solar cells, HTLs and ETLs must have suitable energy levels matching the active layers such

as dyes, Si, Pb-based light harvesting layers, and perovskite films. For example, to fabricate high-performance perovskite solar cells (PSCs), the work function of HTLs and ETLs should have hole and electron transport layers aligned with the valence band edge and conduction band edge of a perovskite. As is well known, the energy levels of NCs can be easily controlled and adjusted by changing their sizes, ligands, and dopants during their synthesis process, which is favourable to satisfy the energy alignment. Meanwhile, the easily-accomplished modifications in NCs mentioned above also favour high mobility to allow carrier transport and form a more effective current circulation path. Furthermore, the transmittance of HTL or ETL based on NCs can be improved during synthesis processes, which leads to less light loss and thus, higher performance of solar cells. Consequently, NCs are a good choice as HTLs and ETLs for efficient solar cells and have gained much attention.

Some researchers found that inserting different IFLs in solar cells could promote the power conversion efficiency (PCE) and stability of the devices. Good IFL can modulate the formation of adjacent layers (especially the perovskite layer in PSCs), optimize energy alignment, and impede charge recombination. As multi-functional IFL, NCs have been extensively investigated due to their compatible properties, such as appropriate morphology for compact, smooth films, gradual energy level to transfer carriers, and self-stability to protect the devices.

Besides acting as a separate functional layer in efficient solar cells, NCs have also been used as additives to improve active layer quality, accelerate carrier transfer, convert infrared or ultraviolet light to visible light, scatter and reflect light, sink heat, and other functions.^{222–258} The addition of NCs could enlarge the grain size of perovskite film, reduce the

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recombination, enhance charge extraction, improve the charge mobility, broaden the spectral response range, and so on.

In this review, functional materials based on NCs for high-performance solar cells are summarized. NCs as HTL, ETL, IFL, and additives for NC-light-harvestor solar cells (NC-LHSCs), PSCs, organic solar cells (OSCs), Si solar cells, and dye-sensitized solar cells (DSSCs) are successively analyzed. In Section 2, NCs as charge transport layers are analyzed in detail. This can provide a deep understanding of the extensive application of NCs in solar cells. As an important functional layer, IFL based on NCs is summarized in the next section. Section 4 describes NCs as efficient additives in different functional layers due to their small sizes and excellent photoelectric properties. Finally, we discuss the existing challenges of NCs for boosting the performance of solar cells and provide some feasible suggestions on these issues, expecting to improve the performance of solar cells based on NCs.

2. Nanocrystals as charge transport layers

In this section, we focus on NCs-based charge transport layers for solar cells, mainly including top/bottom HTL and ETL in n-i-p and p-i-n solar cells.

2.1 Nanocrystals as HTL

As known to us, solar cells work as follows: absorption of sun light, generation and separation of hole–electron pairs, transport of holes through HTL and electrons through ETL, and current produced by the flow of electrons through external circuits. Solar cells using NCs as HTL are not exceptional, and the typical structures of solar cells based on NC HTL are shown in Fig. 1. According to the position of HTL, we call HTL between the ITO/FTO and active layer as bottom HTL while the HTL between metal electrode and active layer as top HTL.

2.1.1 Recent NC HTL. Semiconductor NCs have shown great potential in photoelectronic devices due to their excellent properties. The advances of NC HTLs for solar cells are listed in Table 1, including the size of NCs, device structure, PCE, and stability of solar cells.



Fig. 1 Typical structure of solar cells based on top (left) and bottom (right) NC HTLs.

Lead chalcogenide NCs, especially PbS, have been massively used as efficient top HTL in NC-LHSCs.^{29–56} Additionally, other metal chalcogenide NCs are also excellent choices as top HTL for high-performance perovskite solar cells (PSCs), mainly containing CuInS₂/ZnS (core/shell),⁵⁷ CdZnSe@ZnSe,⁵⁸ Cu₂ZnSnS₄/Se₄,⁵⁹ SnS,⁶⁰ CuInSe₂,⁶¹ Ag–In–Ga–S,⁶² Cu₁₂Sb₄S₁₃,⁶³ Cu₂SnS₃,⁶⁴ CuGaS,⁶⁵ and CuInS₂.⁶⁶ Metal oxide NCs of NiO have shown potential for hole transport on top of the light harvesting layer in PSCs and Si solar cells.^{67–69} Besides NiO, some other metal oxide NCs such as MoO₂,⁷⁰ Co₃O₄,⁷¹ Cu₂O,⁷² CuCrO₂,⁷³ CuGaO₂,⁷⁴ and CsPbI₃ (ref. 75) have been used as efficient top HTL for PSCs due to their excellent properties. It can be noticed that when PbS NCs are used as top HTL in solar cells, the light harvesting layers are mostly based on the PbS/Se family. There are not many perovskite used as light harvest materials when PbS/Se is used as top HTL. Only MAPbI₃ was applied in 2015, and 7.88% PCE was gained.²⁹ We suppose this is because the PbS NCs with long carbon chains or 1,2-ethanedithiol are not good at charge transport. If high-temperature annealing is adopted to enhance the conductivity of PbS, the perovskite underneath will be destroyed. This encourages us to regulate the synthesis or modification of NCs with less or even no charge transfer inhibition capture and improve their electronic properties.

Similar to top HTL, NCs can also be applied as bottom HTL for high-performance solar cells. NCs of PbS,⁷⁶ Cu₂ZnSnS₄,^{77,78} NiO_x and its doped derivatives,^{79–91} CuO,⁹² and ternary oxides of CuCrO₂,^{93,94} CuGaO₂,⁹⁵ NiCo₂O₄,^{96,97} ZnCoO₄,⁹⁸ and doped ternary oxide In:CuCrO₂ (ref. 99) have offered excellent hole transport ability in PSCs and PTB7-Th-based organic solar cells (OSCs).

Ever since demonstrated as efficient HTL by Luther *et al.* in 2008,²⁴⁸ PbS NCs with a 1,2-ethanedithiol (EDT) ligand (named as PbS-EDT or EDT-PbS) have been massively applied for hole transport in solar cells. From the established NC HTLs listed in Table 1, we can find some regular patterns: (i) as top HTL, EDT-linked sulphides were mainly used in NC-LHSCs but were not popular in PSCs. This is because EDT will strongly attack the perovskite materials in the n-i-p device and decrease the device performance.⁶¹ (ii) As bottom HTL, oxides are widely used and sulphides are rare. We speculate that it is (iii) NiO_x with high hole transport quality mostly used to transport holes in PSCs.

The previous light harvesting NC layers are mainly based on the Pb-based chalcogenide family or their mixture. NC-LHSCs using NCs as HTL have gained high PCE above 13%,^{45,50} but this is significantly lower than that of the theoretical value.¹¹ Some strategies were also adopted to modify the light-harvesting NCs, which is not the keynote in this review. The current relatively low PCE of NC-LHSCs may be on account of non-radiative recombination resulting from the high density of surface traps due to some intrinsic properties of NCs, such as high surface-to-volume ratios. Using NC top HTL, the PCE value can be improved. Some oxides, for instance, NiO, Ti-doped MoO₂, Co₃O₄, Cu₂O, CuCrO₂, and CuGaO₂, have acted as excellent top HTL in high-performance PSCs. As shown in Fig. 2a, SnS NCs prepared by the one-pot hot-injection method were utilized as top HTL in efficient and stable



Table 1 Recent advances in selected NC HTLs for solar cells (EDT = 1,2-ethanedithiol, relative humidity = RH)

| | NC | Active layer | PCE (%) | Long-term stability | Ref. | | |
|---------|--|---|---------------------------------------|---|---|--|----|
| Top HTL | PbS-EDT | CH ₃ NH ₃ PbI ₃ PbS | 7.88 | 8% decay after 2 days | 29 | | |
| | | | 11.6 | Null | 30 | | |
| | | | 10.4 | 100%, after 103 days in the dark under ambient conditions | 32 | | |
| | | | 9.44 | ~100%, after 4 months in ambient air | 33 | | |
| | | | 13.2 | Null | 37 | | |
| | | | 10.4 | ①96%, after baking on a hotplate in air for 120 min; ②97%, after 60 min oxygen plasma treatment | 38 | | |
| | | | 13.3 | Null | 39 | | |
| | | | 10.5 | Null | 40 | | |
| | | | 13.0 | Null | 41 | | |
| | | | | PbS-PbI ₂ | 11.2 ± 0.22 | Nearly no drop of PCE after 180 h under continuous heating at 85 °C in ambient air >90, after 600 h under ambient condition | 44 |
| | | | | | 11.29 | | 45 |
| | | | | PbS:F | 12.7 | Null | 46 |
| | | | | PbX ₂ -PbS | 8.16 | Null | 47 |
| | | | | | 10.35 | Null | 48 |
| | | | | | 10.6 | Null | 49 |
| | | | PbS-PbX ₂ -KI ₃ | 12.1 | 94%, after 20 h continuous operation in air | 50 | |
| | | | PbSe-PbS | 1.24 (infrared PCE) | ~95%, after 25 days in air | 51 | |
| | | | PbSe-PbI ₂ | 10.4 | 90%, after 30 days in ambient condition | 51 | |
| | | | CsMAFA-PbS | 11.3 | 96%, after 1200 h shelf storage | 53 | |
| | | | MAPbI ₃ -PbS | 9.5 | 95%, after 2 months in ambient environment | 54 | |
| | | | Sb ₂ Se ₃ | 6.5 (certified) | Null | 55 | |
| | | | KPbS | 12.6 | 83%, after 300 h under continuous operation at MPP in ambient air | 56 | |
| | | | CuInS ₂ /ZnS core/shell | MAPbI ₃ | 8.38 | Null | 57 |
| | | | CdZnSe@ZnSe | CdZnSe@ZnSe | 8.65 | Null | 58 |
| | | | Cu ₂ ZnSnSe ₄ | MAPbI ₃ | 9.72 | Null | 59 |
| | | | Cu ₂ ZnSnS ₄ | | 10.72 | | |
| | | | SnS | (CsPbI ₃) _{0.05} (FAPbI ₃) _{0.79} (MAPbI ₃) _{0.16} (PbI ₃) _{0.03} | 13.7 | ①99%, after 1000 h storage in air; ②75%, after 500 h under continuous 1 sun illumination in a N ₂ atmosphere at 25 °C | 60 |
| | CuInSe ₂ | MAFAPbClBrI | 12.8 | 78%, after 96 h in air | 61 | | |
| | Ag-In-Ga-S | CsPbBr ₃ | 8.46 | 96.1%, after 240 h in air | 62 | | |
| | Cu ₁₂ Sb ₄ S ₁₃ | CsPbI ₃ | 10.02 | 94%, after storage in ambient air for 360 h | 63 | | |
| | Cu ₂ SnS ₃ | Cs _{0.05} (MA _{0.17} -FA _{0.83}) _{0.95} Pb(I _{0.83} Br _{0.17}) ₃ | 13.01 | 90%, after 1200 h in an ambient atmosphere | 64 | | |
| | CuGaS | (FAPbI ₃) _{1-x} (MAPbBr ₃) _x | 17.56 | 81%, aging for 30 days | 65 | | |
| | CuInS ₂ | (FAPbI ₃) _{1-x} (MAPbBr ₃) _x | 18.81 | 91%, aging for 30 days | 66 | | |
| | NiO | MAPbI ₃ | 6.2 | Null | 67 | | |
| | | MAPbI ₃ NCs | 10.89 | Null | 68 | | |
| | Ti-doped MoO ₂ | MAPbI ₃ | 15.8 | ~95%, after 15 days with 50–70% RH | 70 | | |
| | Co ₃ O ₄ | MAPbI ₃ | 13.27 | Up to 2500 hours under ambient conditions | 71 | | |
| | Cu ₂ O | Cs _{0.05} FA _{0.81} MA _{0.14} PbI _{2.55} Br _{0.45} | 18.9 | 80%, after 30 days in air with ~30% RH | 72 | | |
| | CuCrO ₂ | Cs _{0.05} (MA _{0.15} FA _{0.85}) _{0.95} Pb(I _{0.85} Br _{0.15}) ₃ | 16.68 | 88%, after 500 h at the MPP under one sun and a N ₂ atmosphere | 73 | | |
| | CuGaO ₂ | MAPbI ₃ | 18.51 | >85%, after 30 days at 25 °C with 30–55% humidity without encapsulation | 74 | | |
| | CsPbI ₃ | MAPbI ₃ | 17.0 | Null | 75 | | |



Table 1 (Contd.)

| | NC | Active layer | PCE (%) | Long-term stability | Ref. | |
|--------|------------------------------------|---|--------------------------------------|---|---|----|
| Bottom | PbS | MAPbI ₃ | 7.5 | Null | 76 | |
| HTL | Cu ₂ ZnSnS ₄ | MAPbI ₃ | 15.4 | Null | 77 | |
| | | | 6.02 | 87%, after 43 days in N ₂ atmosphere | 78 | |
| | Ni–NiO core–shell | P3HT | 0.86 | Null | 79 | |
| | NiO _x | Cs _{0.08} (MA _{0.17} FA _{0.83}) _{0.92} | 12.8 | Null | 81 | |
| | | Pb(I _{0.83} Br _{0.17}) ₃ | | | | |
| | | MAPbI ₃ | 16.1 | 90%, after 60 days in air at RT | 84 | |
| | | Cs _{0.05} (MA _{0.17} FA _{0.83}) _{0.95} | 18.6 | >80%, after 1000 h | 85 | |
| | | Pb(I _{0.9} Br _{0.1}) ₃ | | | | |
| | | MAPbI ₃ | 17.60 | 93%, after 30 days | 86 | |
| | | | 1.02 cm ² : | 90%, after 500 h in the thermal aging test | 87 | |
| | | | 18.49 (rigid) | (85 °C, 85% RH) | | |
| | | | and 15.89 | | | |
| | | | (flexible) | | | |
| | | Cu:NiO _x | | 15.01 | 86%, after 1 month in an ambient environment at 25 °C with about 40% humidity | 88 |
| | | | | (flexible, >1 cm ²) | | |
| | | (Li,Cu):NiO _x | MAPbI _{3-x} Cl _x | 18.3 | Null | 89 |
| | | NiO _x | CsPbI _x Br _{3-x} | 20.80 | 95%, after 60 days of storage | 90 |
| | CuO | MAPbI ₃ | 16.1 | 85%, after 350 h light soaking | 91 | |
| | CuCrO ₂ | MAPbI ₃ | 15.3 | Null | 92 | |
| | | | 19.0 | ~90, after 30 days in an Ar-filled dry glove box and continuously irradiated by a UV optical fiber with 5 mW cm ⁻² | 94 | |
| | CuGaO ₂ | | 15.6 | Null | 95 | |
| | NiCo ₂ O ₄ | MAPbI _{3-x} Cl _x | 18.23 | ~90%, after 500 h illumination at AM 1.5G | 96 | |
| | ZnCo ₂ O ₄ | PTB7-Th:PC ₇₁ BM | 9.37 | >60%, after 60 h in ambient environment with 50% RH without capsulation | 98 | |
| | | MAPbI _{3-x} Cl _x | 18.14 | >60%, after 110 h in ambient environment with capsulation and under continuous 1 sun illumination soaking | | |
| | In:CuCrO ₂ | Cs _{0.05} (MA _{0.15} FA _{0.85}) _{0.95} | 20.54 | ~90%, after 800 h of continuous radiation in glovebox | 99 | |
| | | Pb(I _{0.85} Br _{0.15}) ₃ | | | | |

(CsPbI₃)_{0.05}(FAPbI₃)_{0.79}(MAPbI₃)_{0.16} PSCs. The high PCE mainly resulted from good surface coverage and an excellent hole extraction ability demonstrated by Nyquist plots. Additionally, SnS-based PSC presented better air stability than the 2,2',7,7'-tetrakis[*N,N*-di(4-methoxyphenyl)amino]-9,9'-spirobifluorene (spiro-OMeTAD)-based device. Surface-modified Cu₂O NCs boosted the efficiency of PSC to 18.9% with distinctly better stability than the reference device based on spiro-OMeTAD.⁶¹ One important reason is the difference in hydrophobicities illustrated by water contact angles in Fig. 2b. Ternary oxide CuGaO₂NCs with promising photoelectronic properties boosted the n-i-p PSCs with higher PCE and stability than spiro-OMeTAD (Fig. 2c).⁷⁵

In n-i-p type solar cells, NiO_x and its doped family oxide NCs are the most popular NC HTLs because of their facile synthesis and outstanding photoelectronic properties.^{86,101} Meanwhile, sulphides of PbS and Cu₂ZnSnS₄ together with multi basic oxides of CuCrO₂, CuGaO₂, NiCo₂O₄, ZnCo₂O₄, and In:CuCrO₂ are valuable substitutes for NiO_x family. Ligand-free NiO_x NCs in ethanol (E-NiO_x) are spin-coated onto a substrate to form a smooth and compact NiO_x film that has good hole extraction capability. As seen in Fig. 3a, this E-NiO_x bottom HTL can be

used both in rigid and flexible PSC, producing high PCE and stability. Similar to top HTL, ternary oxide NCs like CuCrO₂ were also utilized as bottom HTL for high-performance solar cells. The low-temperature solution-processed CuCrO₂ NCs provide suitable electronic structure, charge carrier transport properties, and greater UV light-harvesting, demonstrating its potential as an efficient HTL for highly efficient and photostable n-i-p PSCs (Fig. 3b).

2.1.2 Advantages of NC HTL. One important inherent advantage of semiconductor NCs is their bandgap variation along with modification. The conduction band, valence band, and Fermi level of PbS NCs can be modified by changing surface ligands (Fig. 4), thus enhancing the performance of solar cells.²⁵² Fig. 4 shows that the energy level of PbS NCs is easily changed in a large range by different ligands, facilitating energy matching with the light-harvesting layer and other functional layers. Compared with mostly used organic HTLs of spiro-OMeTAD, poly(3,4-ethylenedioxythiophene):poly(styrene-sulfonate) (PEDOT:PSS) and poly[bis(4-phenyl)(2,4,6-trimethylphenyl)amine] (PTAA), inorganic NCs show higher stability with good hole transport ability, suggesting great potential for boosting solar cell performance. Equally



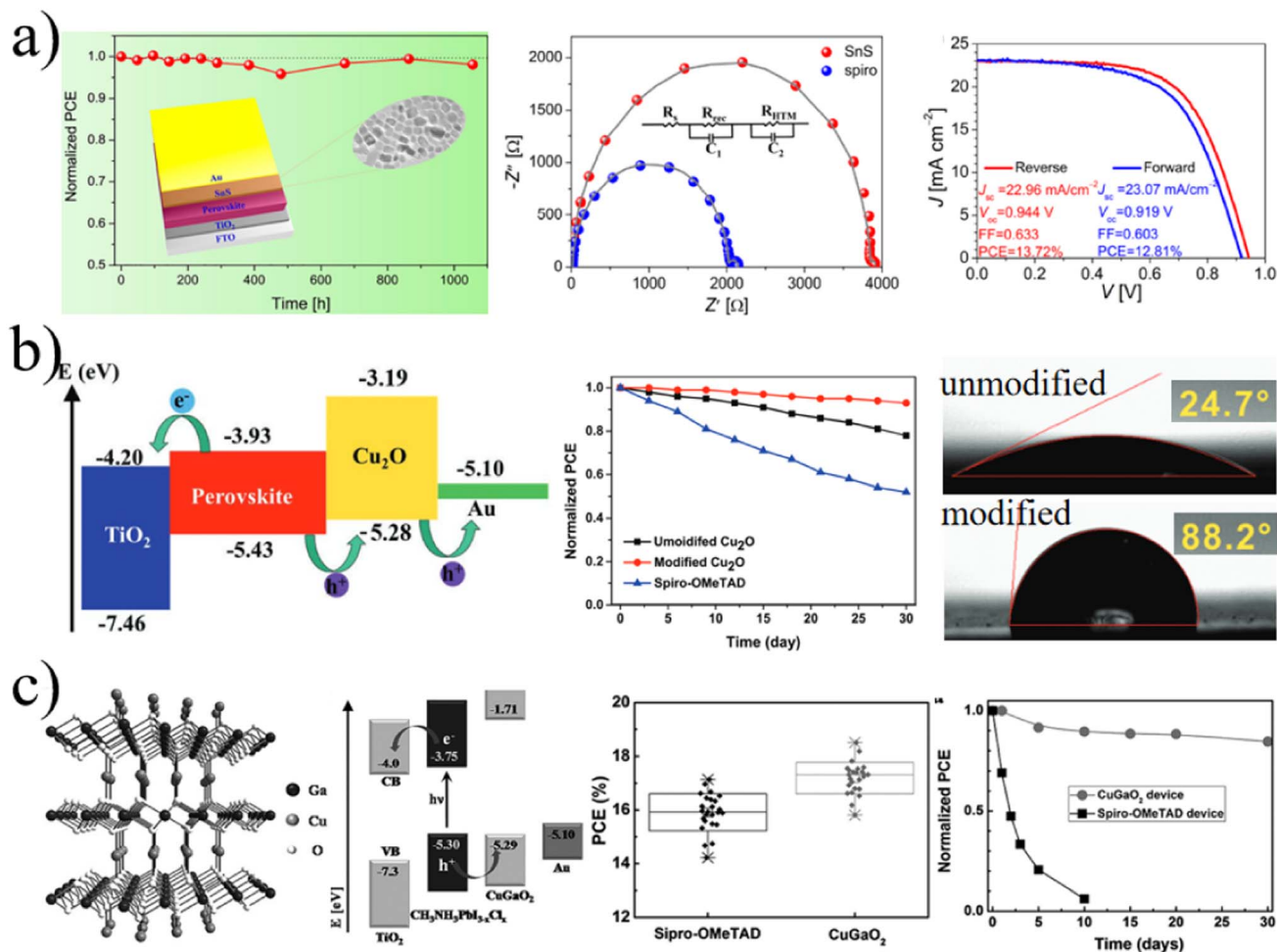


Fig. 2 (a) Evolution of PCE over time of the unencapsulated SnS-based PSCs in the ambient air of ~30–50% humidity, Nyquist plots at 0.9 V forward bias measured in the dark, forward, and reverse J – V curves of champion PSCs based on SnS. (b) Schematic view of PSC configuration, device performance durability of PSCs based on different HTLs in ambient air for 30 days, and water contact angles of unmodified and modified Cu_2O . (c) Schematic illustration of the crystal structure of CuGaO_2 , device architecture of a regular PSC based on CuGaO_2 , standard deviations of PCEs to evaluate reproducibility by statistics of 50 devices based on CuGaO_2 and Spiro-OMeTAD.⁶¹ Copyright 2019, American Chemical Society. (b) Adapted with permission.⁷⁵ Copyright 2019, Wiley-VCH. (c) Adapted with permission.⁷⁵ Copyright 2017, Wiley-VCH.

important, facile synthesis and low cost would be helpful for the commercialization of new-generation solar cells.

2.1.3 Potential NC HTL. To further develop more strategies for fabricating high-performance solar cells and boost the device PCE and stability, we should find more potential NCs for efficient hole transport in solar cells. According to the previous reports and our understanding, excellent NC HTLs should satisfy the following requirements: (i) matched energy level alignments with other functional layers; (ii) high hole mobility and conductivity; (iii) enhancing the quality of adjacent layers; (iv) intrinsic resistance to heat, light and water; (v) convenient fabrication with low cost; and (vi) high transmittance for bottom HTL and reflectivity for top HTL. NCs have many good properties such as easily-controlled energy level, excellent spreading and filling ability due to their small sizes, stable intrinsic structure, skilled synthesis process, and variant surface ligand. Considering the above rules and the advantages

of NCs, besides the existing NC HTLs, some other p-type sulphide and oxide NCs have huge potential for efficient and stable solar cells. Additionally, semiconductor NCs with enhanced hole-transporting ability by p-type doping are also good alternatives.

2.2 Nanocrystals as ETL

2.2.1 Recent advances of NC ETL. As important as HTL, ETL is also of great significance for high-performance solar cells to transport electrons and block holes, and it acts as well as a trap passivating layer and water/oxygen preventing layer. The typical structure of solar cells based on NC ETL is shown in Fig. 5.

ZnO is good at electron transport in photoelectrical devices due to excellent properties such as bandgap (3.3 eV), low cost, high electron mobility ($\sim 10^{-5}$ – $10^2 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$), and matching energy levels.^{100,101} ZnO NCs with different sizes have been used

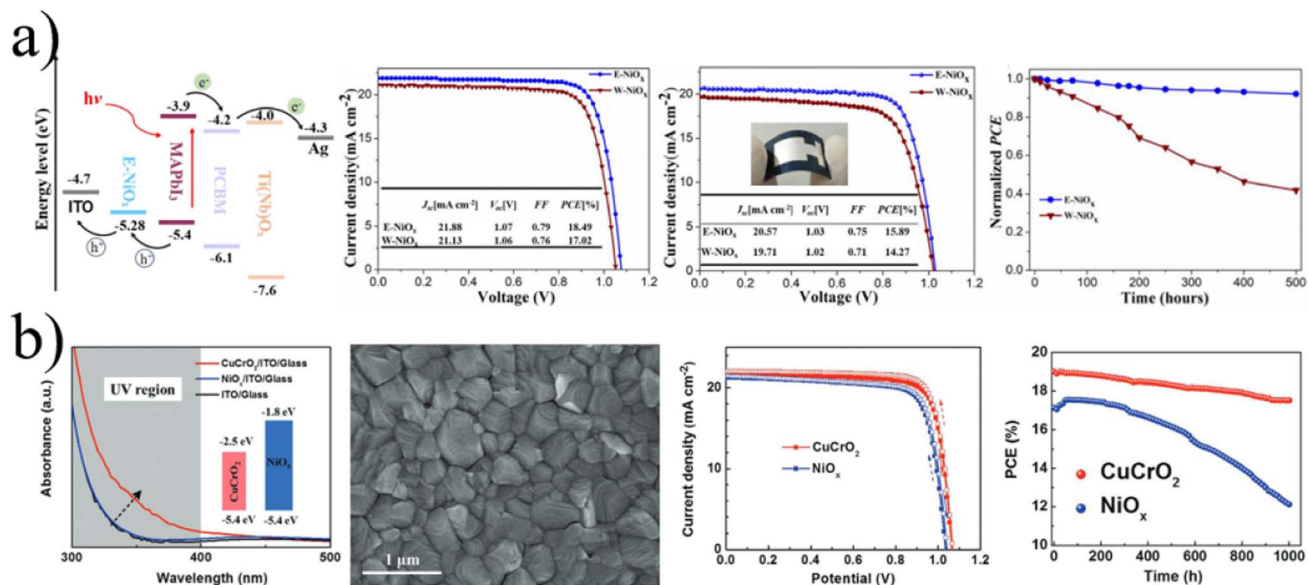


Fig. 3 (a) Energy level diagram of the materials used in the device, J - V curves of rigid and flexible PSCs, normalized PCE. (b) UV-vis spectra of the CuCrO₂ and NiO_x layer with optimum thickness with energy level in the inset. Adapted with permission.^{87,94} Copyright 2018, Wiley-VCH.

as efficient top ETL in NC-LHSCs, OSCs, and PSCs.^{43,84,85,91,101-108} TiO₂ and SnO₂NCs are as popular as ZnO for electron transport due to their outstanding photoelectronic properties of high mobility and conductivity.²⁵⁰ Certainly, these oxide NCs can be modified by doping, ligand changing, and other strategies. Tetrabutylammonium hydroxide (TBAOH)-capped metal oxide NCs for SnO₂ also extend to TiO₂, ITO and CeO₂NCs as top ETL for PSCs.¹⁰⁸ TiO₂NCs have always been as the top ETL for PSCs.¹⁰⁹⁻¹¹¹ CeO_x,¹¹² In₂O₃ and its Sn doped derivative formed bilayer ETL,¹¹³ and CdSe¹¹⁴ were also used for high-performance n-i-p PSCs. As efficient bottom ETL, modified TiO₂ by Sn, Al, Co, Cu, and N doping and N, F and S co-doped graphene NCs were widely used in dye-sensitized solar cells (DSSCs) based on N719 and N3 (*cis*-Ru(H₂dcbpy)₂(NCS)₂, H₂dcbpy = 4,4'-dicarboxy-2,2'-bipyridyl).¹¹⁵⁻¹²⁰ Additionally, TiO₂, CdS NCs-modified TiO₂, and Nb-doped TiO₂NCs were applied for electron transport in PSCs with high PCE and stability.¹²¹⁻¹²³ Meanwhile,

TiO₂NCs have been widely applied in n-i-p solar cells using chalcogenide NC as light harvesters, such as CdSe, CdS, and PbS.¹²⁴⁻¹³⁰ Similarly, ZnO NCs were used as ETL for n-i-p PbS-

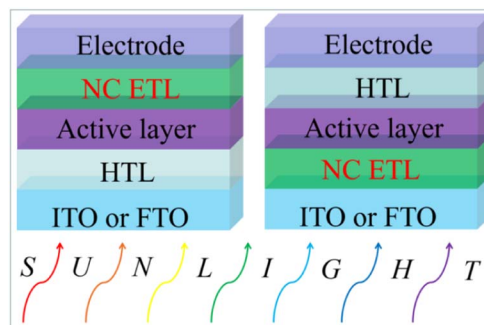


Fig. 5 Structure of solar cells based on top (left) and bottom (right) NC ETLS.

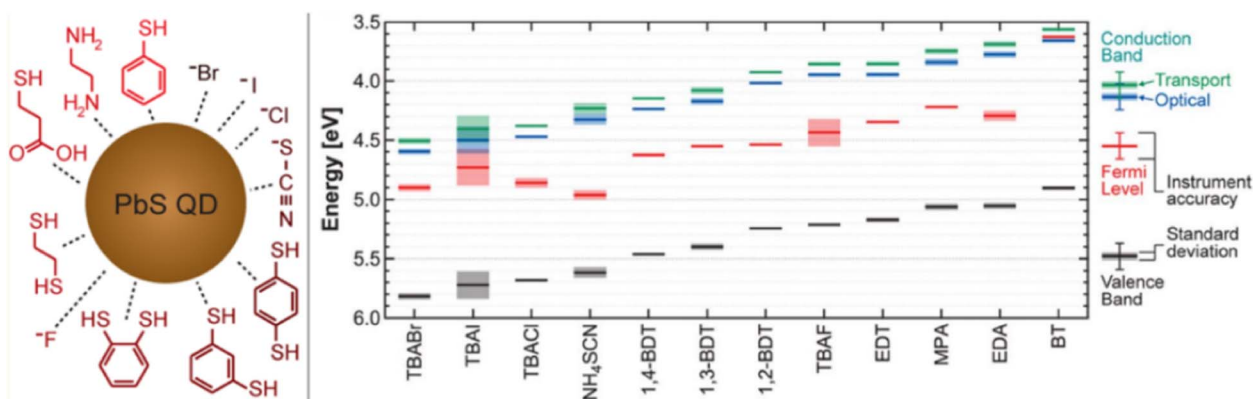


Fig. 4 Energy band position of PbS NC films for different surface ligands. Adapted with permission.²⁴⁹ Copyright 2014, American Chemical Society.



Table 2 Recent advances in NC ETLs (bathocuproine = BCP)

| | NC | Active layer | PCE (%) | Long-term stability | Ref. | |
|---|---|--|---|--|---|-----|
| Top ETL | ZnO | PbS–PbX ₂ | 10.35 | Null | 43 | |
| | | PCDTBT:PC ₆₁ BM | 2.66 | Null | 100 | |
| | | CsPbI ₃ NCS | 13.1 | 80%, after 40 h under 25 °C with 30–40% RH | 103 | |
| | | MAPbI ₃ | 17.2 | 66%, after 120 days stored in air | 105 | |
| | | MAPbI ₃ | 16.1 | 90% after 60 days in air at RT | 84 | |
| | | Cs _{0.05} (MA _{0.17} FA _{0.83}) _{0.95} Pb(I _{0.9} Br _{0.1}) ₃ | 18.6 | >80% after 1000 h | 85 | |
| | | CsPbI _x Br _{3-x} | 16.1 | 85%, after 350 h light soaking | 91 | |
| | | Ag modified BCP:ZnO | MAPbI ₃ | 15.5 | Null | 106 |
| | | In:ZnO | MAPbI ₃ | 16.2 | 85% after 460 h of light soaking | 107 |
| | | TBAOH-SnO ₂ | MAPbI ₃ | 18.77 | 90% after aging at 45 °C for 240 h, followed by 65 °C for 240 h and 85 °C for 240 h | 108 |
| | TiO ₂ | Cs _{0.05} (MA _{0.15} FA _{0.85}) _{0.95} Pb(I _{0.85} Br _{0.15}) ₃ | 20.5 | ~90% after 350 h MPP tracking test | 109 | |
| | Carbide-TiO ₂ | CsPbI ₂ Br | 14.8 | ①>94%, after 1000 h at 85 °C in dark under N ₂ ; ②>90%, after 1000 h at 60 °C under continuous illumination | 110 | |
| | CeO _x | MAPbI ₃ | 16.7 | 100%, after 200 h in air with 30% RH | 112 | |
| | Sn:In ₂ O ₃ /In ₂ O ₃ (bilayer) | Cs _{0.05} (MA _{0.15} FA _{0.85}) _{0.95} Pb(I _{0.85} Br _{0.15}) ₃ | 20.65 | ①91.9% after 69 days under 85 °C; ②91.8% after 2000 h, 12 h continuous 1 sun illumination and then 12 h interval in the dark | 113 | |
| | Bottom ETL | CdSe | MAPbI ₃ | 15.1 | Null | 114 |
| | | Sn:TiO ₂ | N719 | 6.24 | Null | 115 |
| | | Al:TiO ₂ | | 4.27 | Null | 116 |
| | | Co:TiO ₂ | | 4.85 | Null | 117 |
| | | Ti _{0.94} Cu _{0.06} O ₂ | N3/electrolyte | 6.51 | Null | 118 |
| | | TiO ₂ modified by N, F and S, co-doped graphene NCS | N719 | 11.7 | ~85.5, after one month | 120 |
| TiO ₂ | | Cs–FA–MA mixed cation perovskite | 19.03 | 84%, after 30 days | 121 | |
| CdS NCS-modified TiO ₂ | | MAPbI ₃ | 8.16 | Null | 122 | |
| Nb-doped TiO ₂ | | Cs _{0.05} (MA _{0.15} FA _{0.85}) _{0.95} Pb(I _{0.85} Br _{0.15}) ₃ | 18.97 | Null | 123 | |
| TiO ₂ | | CdS | 4.59 | Null | 125 | |
| Cu ₂ O doped TiO ₂ | | CdSe/CdS/ZnS/electrolyte | 3.01 | Null | 126 | |
| TiO ₂ | | Mn–CdSe | 3.55 | Null | 128 | |
| TiO ₂ | | CdSe/ZnS/SiO ₂ /Cu ₂ S | 4.00 | Null | 129 | |
| Cl@ZnO | | PbS | 11.6 | Null | 30 | |
| ZnO | | PbX ₂ –PbS | 9.5 | 95%, after 2 months in ambient environment | 33 | |
| MgZnO | | PbS | 10.4 | 100%, after 103 days in the dark under ambient conditions | 32 | |
| ZnO | | Lead halide-PbS | 12.7 | Null | 46 | |
| ZnO | | PbS | 13.1 ± 0.1 | Null | 37 | |
| ZnO | | PbS NC | 12.44 | Null | 140 | |
| Cs-ZnO | | PbS | 10.43 | 97%, after 3 months under 20 °C and 30% RH without any encapsulation | 144 | |
| ZnO | CsPbBr ₃ –CsPb ₂ Br ₅ | 6.81 | No detectable decay after 100 days under 25 °C and 45% RH | 146 | | |
| ZnO | PTB7-Th:PC ₇₁ BM | 12.02 | Null | 147 | | |
| Na–ZnO | p-DTS(FBTTh ₂) ₂ :PC ₇₀ BM | 9.2 | 90%, after 28 h | 149 | | |
| SnO ₂ | N719 | 3.2 | Null | 151 | | |
| Ni:SnO ₂ | | 3.6 | | | | |
| Zn:SnO ₂ | | 4.2 | | | | |
| SnO ₂ | Eosin-Y | 3.89 | Null | 155 | | |
| Sn _{0.92} O ₂ :Sb _{0.08} | | 4.15 | Null | 156 | | |



Table 2 (Contd.)

| NC | Active layer | PCE (%) | Long-term stability | Ref. | |
|--|--|--|--|--|---------------------------|
| SnO ₂ | PBDR-T & ITIC-4 | 12.023 | ①>90%, up to 75 h after exposure to an ambient atmosphere with continuous illumination; ②>95%, after storage in N ₂ for 200 h with continuous illumination | 157 | |
| | PM6:Y6 | 14.9 | 81%, after 15 days stored in the air at RM without encapsulation | 158 | |
| | PTB7-Th:PC ₇₁ BM PM7:ITC6-4F PM6:Y6 | 10.30 13.93 15.38 | Null Null 94.3%, after 100 h light aging | 159 | |
| Cl@SnO ₂ | CsPbI ₃ NCs | 14.5 | 80%, without encapsulation under 1-sun light soaking and 50% relative humidity for 8 h | 27 | |
| | Ga:SnO ₂ SnO ₂ | Cs _{0.05} (MA _{0.17} FA _{0.83}) _{0.95} Pb(I _{0.83} Br _{0.17}) ₃ CsPbI ₃ /FAPbI ₃ | 18.18 16.07 | Null 96%, after 1000 h in ambient storage | 161 162 |
| SnO ₂ /TiO ₂ (bilayer) | Cs _x (MA _{0.17} FA _{0.83}) _(100-x) Pb(I _{0.83} Br _{0.17}) ₃ | 17.92 | 89%, after 2500 h stored under 20 ± 5% RH | 163 | |
| | MAPbI ₃ | 13.90 (flexible device) | Null | 164 | |
| | (CsPbI ₃) _{0.04} (FAPbI ₃) _{0.82} (MAPbBr ₃) _{0.14} | 20.34 ± 0.5 | 90%, after 720 h storage | 165 | |
| | Cs _{0.05} (MA _{0.17} FA _{0.83}) _{0.95} Pb(I _{0.83} Br _{0.17}) ₃ FAPbI ₃ | 20.79 25.39 (0.0803 cm ²) | Null ①80% after 1000 h in ambient air at 25% RH and 25 °C without sealing; ②70.5% after 700 h light soaking; ③95% (encapsulated cell) after 100 h MPP tracking and 2 h dark recovery under ambient conditions | 167 168 | |
| | | 23.3 (1 cm ²) | Null | | |
| | | 21.7 (20 cm ²) | Null | | |
| | | 20.6 (64 cm ²) | Null | | |
| | | 15.86 | ①~95%, after 1 month storage in N ₂ glovebox without encapsulation; ②>80%, after 1 month stored under RT and 20–30% RH without encapsulation | 169 | |
| | SnO ₂ /InP–ZnS (bilayer) | PM6:Y6 | 15.22 | >80%, after 500 h in N ₂ without encapsulation | 170 |
| | Ni:Co ₃ S ₄ Ni:Co ₄ S ₃ NiCo ₂ S ₄ Zn ₂ SnO ₄ Y:SrSnO ₃ | N719 FA _{0.85} MA _{0.15} Pb(I _{0.85} Br _{0.15}) ₃ | 6.01 6.82 7.43 4.9 ± 0.2 19.0 | Null 91%, after 1000 h stored in N ₂ | 171 172 173 |

based NC-LHSCs,^{30,32,35,39,40,44,45,58,131–145} PSCs,¹⁴⁶ and OSCs.^{147–149} SnO NCs as ETL for DSSCs,^{150–156} for OSCs,^{157–159} and for PSCs,^{27,160–168} have been demonstrated. Additionally, a bilayer of SnO₂/TiO₂ (ref. 169) and SnO₂/InP–ZnS¹⁷⁰ were used for PSCs and DSSCs. Ni-doped Co₃S₄ and Co₄S₃ and ternary sulphide NCs of NiCo₂S₄ and Zn₂SnO₄ have been used for DSSCs,^{171,172} while

doped SrSnO₃ NCs for PSCs.¹⁷³ NCs have been used as IFL for NC-LHSCs,^{49,141,174–179} OSCs,^{180–185} DSSCs,^{186–195} PSCs,^{196–212} and Si solar cells.^{213–220} FAPbBr₃ perovskite NCs have been used as a multifunctional luminescent-downshifting passivation layer for GaAs solar cells.²²¹



Explored dopants (orange)
Potential dopants (turquoise)

* Lanthanide series
** Actinide series

Fig. 6 Summary of the explored and potential elements as dopants in TiO_2 -based electron transporters for PSCs in the periodic table, as in 2017.²⁵³ Copyright 2017, Wiley-VCH.

From the reported literature listed in Table 2, selenide NCs of CdSe, and doped sulfide NCs of $\text{Ni}:\text{Co}_2\text{S}_4$, $\text{Ni}:\text{Co}_4\text{S}_3$, and $\text{Ni}:\text{Co}_2\text{S}_4$ have shown their potential, suggesting more substitutes for traditional NC ETL. The advantages of NC ETL and some potential NCs suitable as ETLs are discussed in the following sections.

2.2.2 Advantages of NC ETL. Compared with common organic ETLs such as fullerenes ($\text{C}_{60}/\text{C}_{70}$) and phenyl-C61-butyric acid methyl ester (PCBM), semiconductor NCs can easily overcome the shortcomings of poor stability, high cost, and unsuitable energy levels. In detail, PCBM film degrades at 85°C , indicating its thermal instability.¹¹⁰ The cost of synthesis and purification for organic electron transport materials is higher than most semiconductor NCs.²⁵² Moreover, the semiconductor NCs can offer adjustable energy levels by easily

controlling the size. The above advantages strongly demonstrate that semiconductor NCs are a very good choice as efficient ETL in high-performance solar cells.

2.2.3 Potential NC ETL. Thanks to their unique application advantages in solar cells, NC ETLs have been widely used, boosting the devices to higher PCE and stability. More oxide and chalcogenide NCs as well as their doped congeners are anticipated alternatives. As we know, TiO_2 NCs always act as splendid ETL in solar cells. The properties of TiO_2 NCs can also be improved by doping, enhancing the device performance. As shown in Fig. 6, many elements were successfully doped in TiO_2 as ETL for PSCs. Meanwhile, more elements are potential dopants for high-quality TiO_2 and this suggests that there is much room for doped- TiO_2 NC ETL. Additionally, we reasonably



Fig. 7 Typical position sketch of interfacial layers in solar cells.



Table 3 Recent advances in selected NCIFLs

| | IFL and its adjacent layers | PCE (%) | Functions | Ref. |
|---|---|---------|--|------|
| PbCdS | TiO ₂ /PbCdS/CdS | 3.35 | Enhance light absorption; suppress interfacial recombination | 174 |
| CdS + amine/ZnS | TiO ₂ :Al ³⁺ /CdS + amine/ZnS/ electrolyte/CuS | 2.4 | Decrease electron–hole recombination | 175 |
| Cu _x S | CIZS + mp-TiO ₂ /electrolyte/Cu _x S/ electrode | 1.13 | Null | 176 |
| CdSe | ZnO/CdSe/PbS | 7.9 | Suppress interface recombination; contribute additional photogenerated carriers | 141 |
| NiO | PbS-EDT/NiO/Au | 10.4 | Improve hole extraction efficiency; suppress the penetration of moisture and oxygen; good band alignment | 49 |
| PbS-EDT | PbS-TBAI/PbS-EDT/P3HT | 8.7 | Adjust the valence band; improve charge transfer | 177 |
| CsPbBr ₃ | PbSe-MPA/CsPbBr ₃ /Au | 7.22 | Suppress carrier recombination | 178 |
| ZnO | Mg-doped ZnO/ZnO/PbS | 7.06 | Decrease the interface recombination | 179 |
| CdSe | ZnO/CdSe/P3HT:PCBM | 2.25 | Increase conductivity; electron transport and hole block | 180 |
| CuInS ₂ -ZnS | TiO ₂ /CuInS ₂ -ZnS/PCDTBT:PC ₇₁ BM | 7.01 | Increase the electron extraction; reduce impedance | 181 |
| CdSe | P3HT:PCBM/CdSe/Al | 3.08 | Down-conversion, reduce charge recombination | 182 |
| ZnCdS | TiO ₂ /ZnCdS/PTB7:PC ₇₁ BM | 7.75 | Suppress the recombination; reduce the series resistance | 183 |
| SnO ₂ | ITO/SnO ₂ /ZnO | 7.16 | Enhance optical transmission; reduce energy barrier; suppress carrier recombination | 184 |
| Ag ₂ Se | TiO ₂ /Ag ₂ Se/N719 | 5.89 | Null | 186 |
| CdS | TiO ₂ /CdS/N719 | 7.54 | Suppress the charge recombination; increase the optical absorption | 187 |
| CeO ₂ :Eu ³⁺ | N719/CeO ₂ :Eu ³⁺ /electrolyte | 8.36 | Down-convert UV light to visible light, light scattering | 190 |
| NaGdF ₄ :Eu ³⁺ | FTO/TiO ₂ /N719/electrolyte/Pt/FTO/ NaGdF ₄ :Eu ³⁺ | 9.34 | Act as luminescent down-conversion centers and light scatterers in the ultraviolet and visible domains | 191 |
| CaCe ₂ (MoO ₄) ₄ :Er ³⁺ /Yb ³⁺ | Electrolyte/CaCe ₂ (MoO ₄) ₄ :Er ³⁺ /Yb ³⁺ / Pt | 7.78 | Convert the NIR and UV radiation to visible emissions | 192 |
| NaYF ₄ :20%Yb, 2% Er@NaYF ₄ :7%Eu | N719/NaYF ₄ :20%Yb,2% Er@NaYF ₄ :7%Eu/Pt | 7.664 | Convert NIR and UV lights to visible lights | 193 |
| SrF ₂ :Pr ³⁺ -Yb ³⁺ | FTO/SrF ₂ :Pr ³⁺ -Yb ³⁺ /TiO ₂ -N719 | 9.07 | Absorb blue light and emit green and red light | 194 |
| BaWO ₄ :Pr ³⁺ | TiO ₂ /BaWO ₄ :Pr ³⁺ /N719 | 8.08 | Absorb UV light and emit blue, green, and red light | 195 |
| MAPbBr _{0.9} I _{2.1} | TiO ₂ /MAPbI ₃ /MAPbBr _{0.9} I _{2.1} | 13.32 | Facilitate hole transfer from MAPbI ₃ to HTL | 196 |
| CuInS | MAPbI ₃ /CuInS/spiro-MeOTAD | 13.8 | Enhance charge transfer; suppress charge recombination pathways | 198 |
| MgO | FTO/MgO/SnO ₂ | 18.23 | Smoother surface; less FTO surface defects; suppressed electron–hole recombination | 199 |
| CdS | TiO ₂ /CdS/MAPbI ₃ | 10.52 | Longer electron lifetime; lower charge carrier recombination rate | 200 |
| SnO ₂ | PC ₆₁ BM/SnO ₂ /Al | 19.7 | Block holes; enhance the conductivity; reduce the recombination | 201 |
| Cl-SnO ₂ | FTO/Cl-SnO ₂ /CsMAFAPbI ₃ Br _{3-x} | 17.3 | Fill the pinholes; passivate the trapping defects | 202 |
| FAPbX ₃ | MAPbI ₃ /FAPbX ₃ /C60 | 7.59 | Enhance absorption | 203 |
| PbS | MAPbI ₃ /PbS/spiro-OMeTAD | 19.24 | Enhance hole extraction; retard interfacial recombination; improve perovskite film morphology | 204 |
| CuO _x | NiO _x /CuO _x /MAPbI ₃ | 19.91 | Lead higher transfer efficiency and lower carrier recombination | 205 |
| MAPbBr _{0.9} I _{2.1} | SnO ₂ /MAPbBr ₃ /MAPbBr _{0.9} I _{2.1} | 20.21 | Optimize the energy level; improve hole extraction | 206 |
| Co-CuGaO ₂ | Cs _{0.05} (MA _{0.15} FA _{0.85}) _{0.95} Pb(I _{0.85} Br _{0.15}) ₃ / Co-CuGaO ₂ /spiro-OMeTAD | 20.39 | Reduce the energy gap; prevent direct contact between PVK and oxygen and moisture | 207 |
| MoS ₂ :RGO | MAPbI ₃ /MoS ₂ :RGO/spiro-OMeTAD | 20.12 | Extract holes and block electrons | 208 |
| CsCu ₅ S ₃ | MAFAPbI ₃ /CsCu ₅ S ₃ /spiro-OMeTAD | 22.29 | Favor for energy levels; reduce carrier recombination | 209 |
| Cu _{2-x} S@SiO ₂ @Er ₂ O ₃ | TiO ₂ /Cu _{2-x} S@SiO ₂ @Er ₂ O ₃ /MAPbI ₃ | 17.8 | Upconvert infrared light to visible light | 210 |
| NaYF ₄ :Yb ³⁺ ,Er ³⁺ / @NaYF ₄ :Yb ³⁺ ,Nd ³⁺ | IR-783 + NaYF ₄ :Yb ³⁺ ,Er ³⁺ / @NaYF ₄ :Yb ³⁺ ,Nd ³⁺ + Au/ CsMAFAPbBrI | 20.5 | Convert IR to visible light, scatter light | 212 |
| MoS ₂ | SiO _x /MoS ₂ /MoO _x | 22.8 | Provide electron-blocking and hole-extraction properties | 213 |
| PbS | PbS/c-Si solar cell | 12.6 | Luminescent solar concentrator | 214 |
| CdS | Si solar cell/CdS | 9.37 | Reduce the reflectance spectral ranging from 250 to 1100 nm, passivation, and down-conversion | 216 |



Table 3 (Contd.)

| | IFL and its adjacent layers | PCE (%) | Functions | Ref. |
|--|---|---------------------------------------|---|------|
| $Zn_xCd_{1-x}S-ZnS:Mn$ | Si solar cell/ $Zn_xCd_{1-x}S-ZnS:Mn$ | 14.271 ± 0.268 | Down-conversion | 217 |
| $Cd_{0.5}Zn_{0.5}S-ZnS:Mn$ | Si solar cell/ $Cd_{0.5}Zn_{0.5}S-ZnS:Mn$ | 17.90 | Down-convert UV light of 250–450 nm to yellow-orange light at 583 nm | 218 |
| $NaGdF_4:Ce@NaGdF_4:Nd/Yb@NaYF_4$ | c-Si solar cell/ $NaGdF_4:Ce@NaGdF_4:Nd/Yb@NaYF_4$ | 0.8 (under 254 nm illumination) | Expand the spectrum of quantum cutting in the NIR | 219 |
| $CsPbCl_{1.5}Br_{1.5}:Yb^{3+},Ce^{3+}$ | c-Si solar cell/ $CsPbCl_{1.5}Br_{1.5}:Yb^{3+},Ce^{3+}$ | 21.5 | Larger absorption cross-section, weaker electron-phonon coupling and higher inner luminescent quantum yield | 220 |

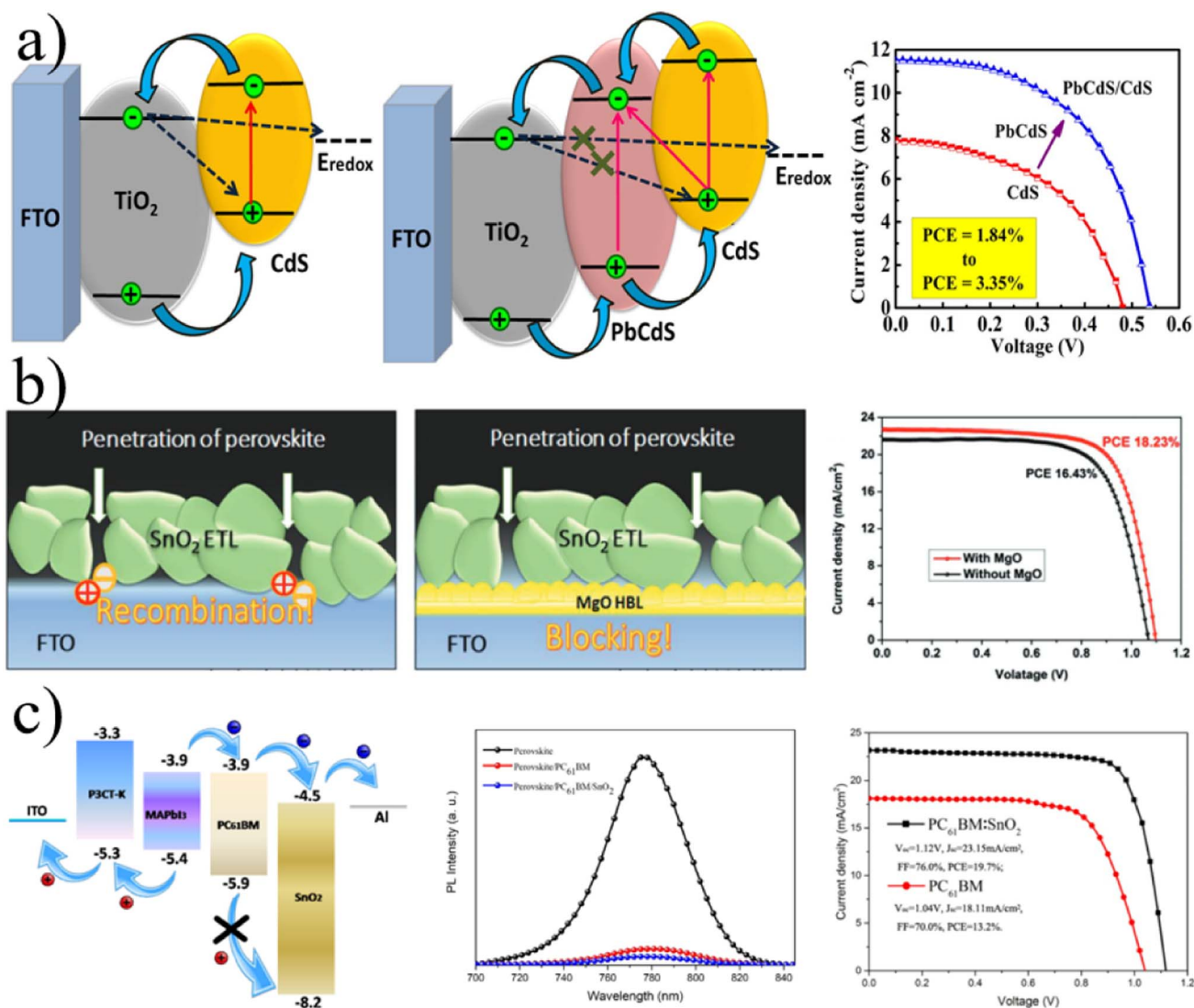


Fig. 8 (a) Schematic illustration of the possible electron transfer process in bare CdS and PbCdS/CdS based solar cells and J – V curves of CdS and PbCdS/CdS based solar cells. (b) The perovskite can directly contact the FTO surface along a shunt pathway in the absence of SnO₂ ETLs; the MgO₂ layer can inhibit the penetration of perovskite reaching the FTO surface, and the best performance of the PSCs with and without MgO. (c) Corresponding energy level diagram of PSCs, steady-state PL spectra of the perovskite film deposited on the PC₆₁BM layer and PC₆₁BM:SnO₂ bilayer, J – V characteristics in the illumination for the devices based on the PC₆₁BM layer and PC₆₁BM:SnO₂ bilayer. (a) Adapted with permission.¹⁷⁴ Copyright 2017, Elsevier. (b) Adapted with permission.¹⁹⁹ Copyright 2017, Wiley-VCH. (c) Adapted with permission.²⁰¹ Copyright 2018, American Chemical Society.



think this strategy is also applicable to other oxide NCs like SnO_2 due to its comparable nature with TiO_2 .

3. Nanocrystals as IFL

Besides HTL and ETL, another essential layer is the interfacial functional layer (IFL). Interfaces play a non-ignorable role in improving both PCE and stability through many paths. The position of a typical IFL is shown in Fig. 7. The IFL can be located at different positions in the solar cells to make different contributions. NCs IFL can enhance light absorption, decrease carrier recombination, improve charge transport ability, reduce impedance, convert ultraviolet (UV) or near-infrared (NIR) light to visible light, enhance optical transmission, decrease trap states of the active layer, and so on. Table 3 shows the recent advances of NC IFLs, and the detailed discussion is as follows.

3.1 Suppressing recombination

As shown in Fig. 7, IFL is a separate layer between the charge transport layer/active layer or charge transport layer/electrode. So, it can convincingly act as a functional layer to prevent hole–electron recombination. Ternary semiconductor NCs of PbCdS were deposited on TiO_2 as an IFL to impede the direct contact between ETL and the active layer of CdS , thus suppressing recombination efficiently and boosting the device PCE significantly (Fig. 8a). As the same, oxide NCs of MgO and SnO_2

film inserted between ETLs and electrodes blocked holes and reduced recombination (Fig. 8b and c).^{199,201}

3.2 Charge transport improvement

As we know, charge transport ability inevitably affects the performance of solar cells. As shown in Fig. 9a, $\text{MAPbBr}_{0.9}\text{I}_{0.1}$ NCs with good energy alignment enhance the hole transport ability and the PCE of the PSCs. Co-CuGaO_2 NCs with ~ 20 nm size were synthesized by hydrothermal method and used for surface passivation at the interface of perovskite and spiro-OMeTAD. Furthermore, the larger bandgap and lower valence band energy of Co-CuGaO_2 reduced the energy gap between Co-CuGaO_2 and perovskite. Considering that the reduced energy gap improved hole conduction and electron blocking, the PCE of PSCs was enhanced from 18.60% to 20.39%.²⁰⁷ MoS_2 NCs were also used to improve hole transport and the device PCE and stability (Fig. 9b).

3.3 Light conversion and harvest enhancement

It is known that the active layer of recent solar cells cannot respond to the whole solar spectrum, resulting in energy loss and relatively low efficiency. Broadening the absorption of the active layer is an efficacious strategy to reduce energy loss and enhance the performance of solar cells. CdS NCs with general Stocks shifts were used in Si solar cells for spectral range

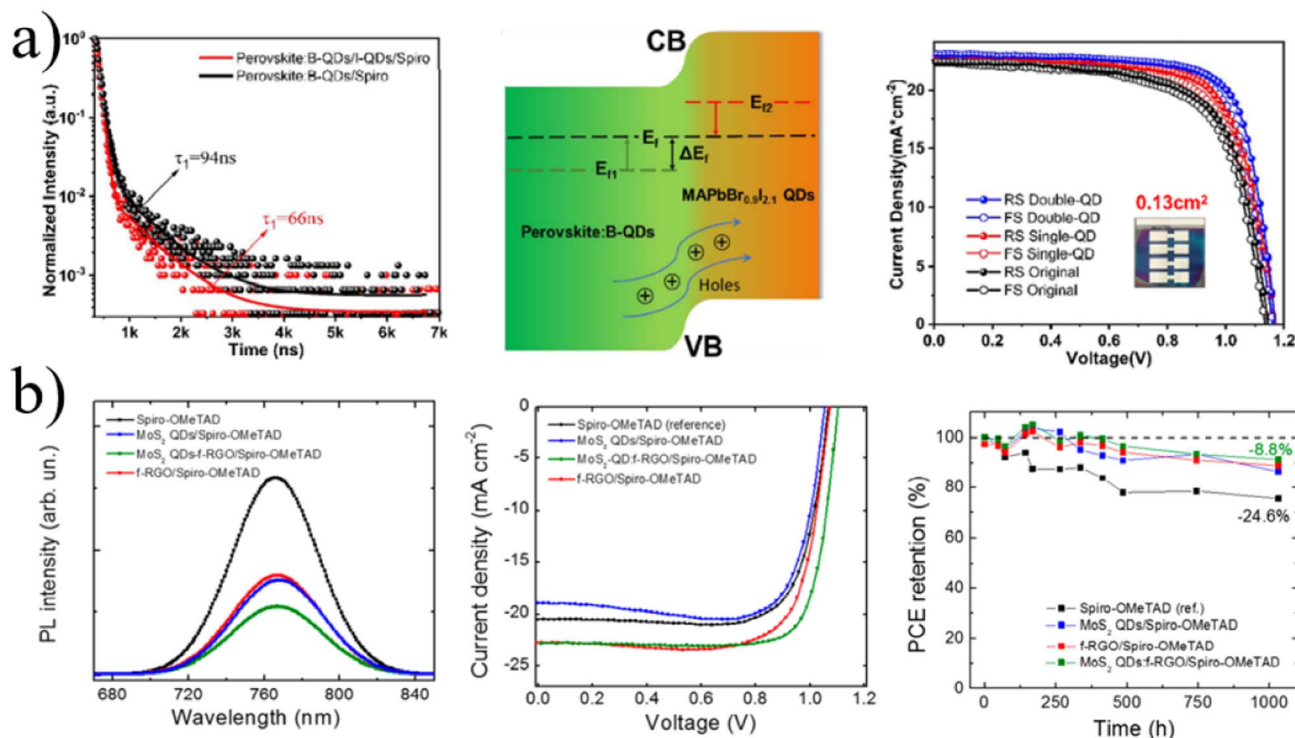


Fig. 9 (a) TRPL spectra of the perovskite film with and without $\text{MAPbBr}_{0.9}\text{I}_{0.1}$ NCs, schematic diagram of band bending in the heterojunction structure formed by the perovskite and $\text{MAPbBr}_{0.9}\text{I}_{0.1}$ NCs. (b) Steady-state PL measurements of $\text{MAPbBr}_{0.9}\text{I}_{0.1}$ after the deposition of spiro-OMeTAD and different IFL/spiro-OMeTAD, I - V characteristics of tested PSCs using different IFLs, normalized PCE trends vs. time extracted by I - V characteristics under 1 sun illumination, periodically acquired during the shelf life test for the PSCs. (a) Adapted with permission.²⁰⁶ Copyright 2020, American Chemical Society. (b) Adapted with permission.²⁰⁸ Copyright 2018, American Chemical Society.



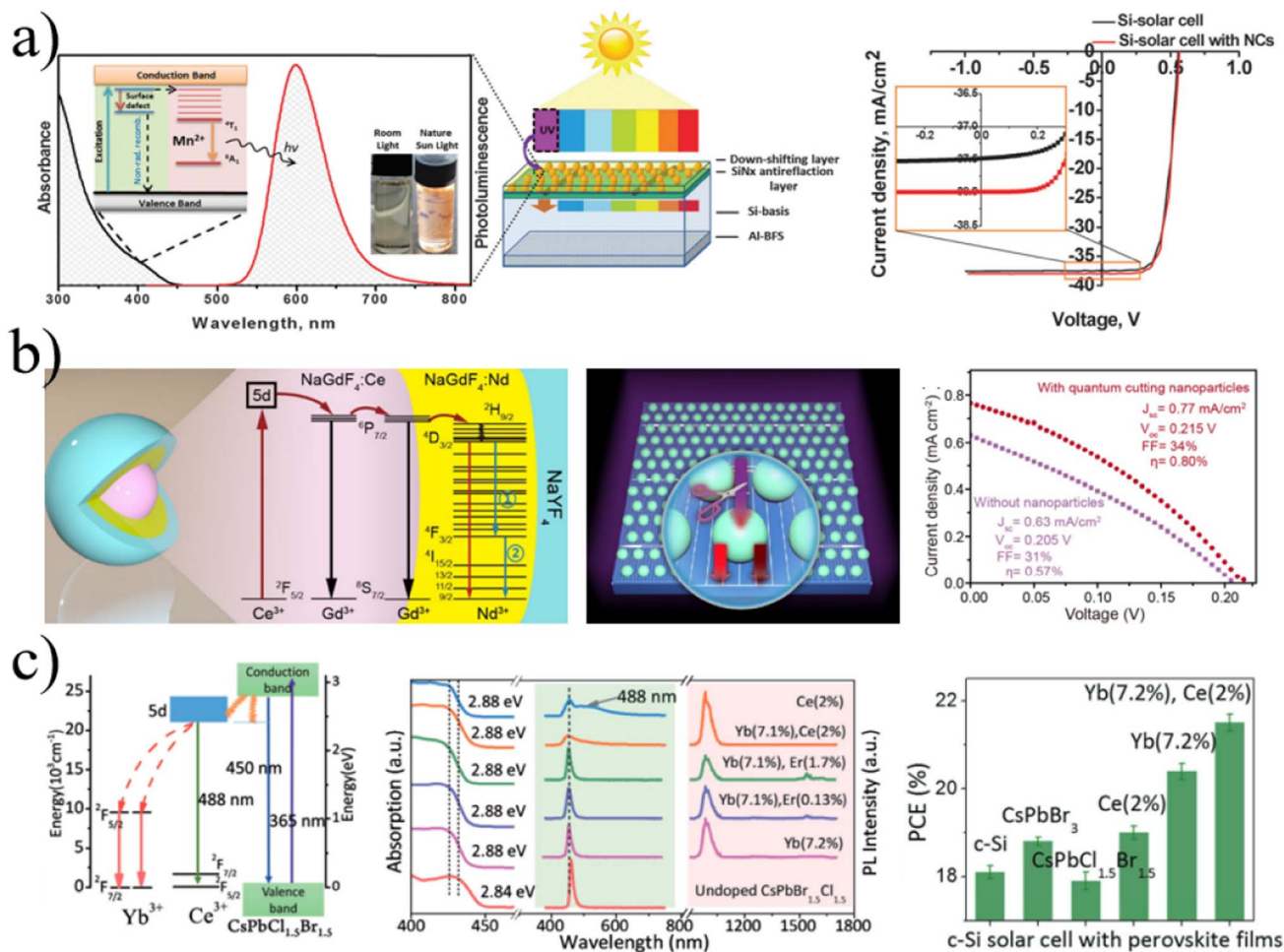


Fig. 10 (a) Scheme of the down-shifting mechanism of the Zn_{0.5}Cd_{0.5}S:Mn (5%)/ZnS NC converter material and the design of proof-of-concept solar cell; J - V curves of the corresponding solar cells. (b) Schematic and proposed energy transfer for Ce³⁺-sensitized quantum cutting in Nd³⁺ ions; schematic design for boosting the energy-harvesting efficiency of c-Si solar cells with quantum cutting nanocrystals; comparison of current density-voltage characteristic for c-Si solar cells with and without a nanocrystal coating layer (the solar cells were illuminated with a 254 nm UV lamp at a power density of 7 mW cm⁻²). (c) Schematic diagram of energy transfer mechanism in the Yb³⁺, Ce³⁺ codoped CsPbCl_{1.5}Br_{1.5}NCs, absorption; visible and near-infrared emission spectra of CsPbCl_{1.5}Br_{1.5} perovskite NCs codoping with different rare earth ions; PCE of Si solar cells with different perovskite NCs. (a) Adapted with permission.²¹⁷ Copyright 2016, the Royal Society of Chemistry. (b) Adapted with permission.²¹⁹ Copyright 2017, American Chemical Society. (c) Adapted with permission.²²⁰ Copyright 2017, Wiley-VCH.

enhancement.²¹⁶ In Fig. 10a, we can see that Mn-doped NCs expand the spectral range response of solar cells by absorbing short-wave lights and emitting the characteristic light around 580 nm, suggesting a larger range of light harvesting by active layer and PCE improvement. Zn_xCd_{1-x}S/ZnS:Mn²⁺ NCs were also used to broaden the light response range of Si solar cells.²¹⁷ Furthermore, Mn-doped semiconductor NCs have a large Stokes shift, avoiding self-absorption and thus reducing energy loss. Sr₂CeO₄ NCs with down-shifting properties could improve the stability of organic P3HT:PCBM solar cells without significant loss of short-circuit current.¹⁸⁵ Certainly, by using NCs with a Stokes shift for expanded light harvesting, the photoluminescence yield and other photoelectronic properties should keep the rules of high-performance solar cells.

Besides the above NCs, rare elements are good at light conversion due to their special energy levels. Undoped and doped NCs based on rare elements were massively applied to

broaden the light response in solar cells and efficiently boost the device performance. As seen in Fig. 10b and c, Yb³⁺, Ce³⁺, and Nd³⁺ based NC layers efficiently convert light and enhance the device performance. Additionally, Eu³⁺, Er³⁺, and Pr³⁺ were also used for efficient solar cells.

3.4 Energy level optimization

To ensure propitious charge transfer among the functional layers in solar cells, un-matched energy levels are a tricky issue that we need to address. One origin of the open-circuit voltage (V_{oc}) loss of NC-LHSC, Si solar cells, PSCs, and OSCs is mainly analyzed quantitatively *via* the energy difference between bandgap and the Schokley-Queisser limit voltage.¹⁵ For n-i-p solar cells, band alignment between the active layer and ETL directly limits the splitting of the quasi-Fermi level. For p-i-n solar cells, the band alignment between HTL and active layer has a great impact on the V_{oc} . The conduct band of recent HTL



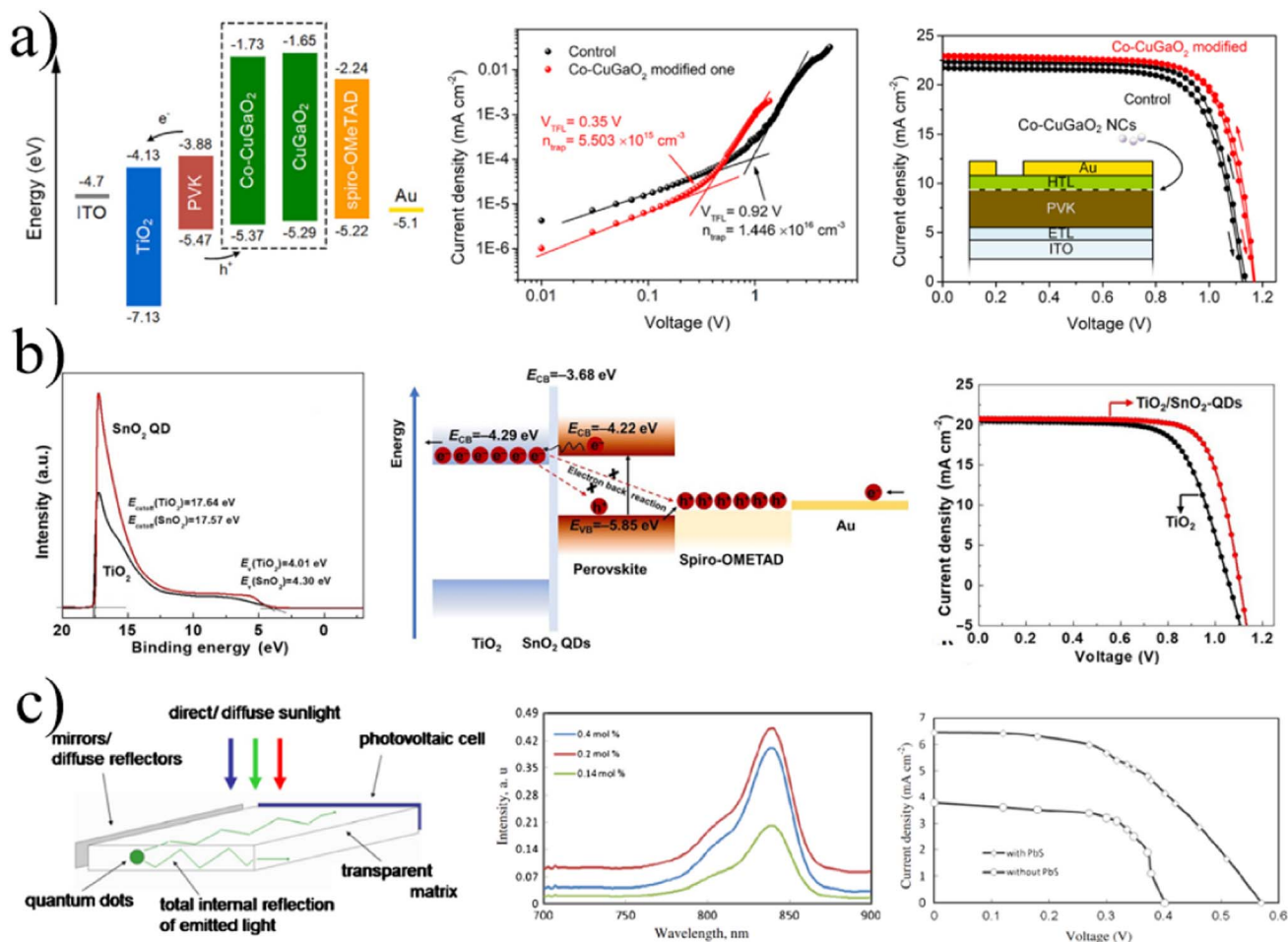


Fig. 11 (a) Energy level diagram of PSCs with the ITO/TiO₂/PVK/Co-CuGaO₂/spiro-OMeTAD/Au structure, dark *I*-*V* curves of devices based on spiro-OMeTAD and Co-CuGaO₂/spiro-OMeTAD, forward and reverse scan *J*-*V* curves based on spiro-OMeTAD and Co-CuGaO₂/spiro-OMeTAD. (b) Band edge alignment and photocarrier dynamics in the resultant device. (c) Schematic illustration of an NC-luminescent solar concentrator, PL spectra of PbS NC-luminescent solar concentrator with different concentrations of PbS, and *J*-*V* curves for solar cells with and without PbS NC-luminescent solar concentrator. (a) Adapted with permission.²⁰⁷ Copyright 2022, Elsevier. (b) Adapted with permission.²⁰² Copyright 2019, Elsevier. (c) Adapted with permission.²¹⁵ Copyright 2015, Springer.

is relatively deep, and the barrier for electron transport is not sufficient, resulting in electron leakage and reducing the device performance. Therefore, energy level is of great importance to improve the performance of solar cells. Shown in Fig. 11a and b, Co-doped CuGaO₂ and SnO₂NCs film were used for energy level optimization for high-performance solar cells, illuminating the large potential of NCs as ITL for reducing V_{oc} loss of solar cells.

3.5 Concentrating luminescent solar radiation

Solar radiation is geographically extensive, but the energy density is not high. So, concentrating solar light for higher density is a feasible strategy to improve solar cell performance. PbS NC luminescent solar concentrator (LSC) was found to show potential advantages over silicon solar cell panels (Fig. 11c). They can reduce the size of solar cells and offer great flexibility in design, which results in cost reduction with any desired shape. One of the attractive LSCs is based on NCS.

3.6 Prevention

The main reason for unstable solar cells is the invasion of oxygen and water. IFL between the active layer and HTL, ETL, or electrode can arrest this invasion to a great degree and increase the stability of solar cells. The above-mentioned IFL of Co-CuGaO₂ NCs in Fig. 11a not only acts as a hole transport accelerator but also prevents the direct contact of perovskite with oxygen and moisture, boosting the stability of the PSCs.²⁰⁷

4. Nanocrystals as efficient additives

Besides an independent layer to improve the performance of solar cells, NCs have also been used as additives for boosting active layer quality, carrier transfer acceleration, spectral response broadening due to plasmonic effect, light conversion, light scattering/reflection, heat sinking, and some other functions. Table 4 lists the recent progress of NCs as efficient additives for high-performance solar cells.



Table 4 Recent advances in NC additives for high-performance solar cells

| NC | Added layer | NC additives and the mixture | PCE (%) | Functions | Ref. |
|--|--------------|---|--------------|--|------|
| SnO ₂ -Sb ₂ O ₃ | Bottom ETL | SnO ₂ -Sb ₂ O ₃ + TiO ₂ | 7.7 | ①Improve the electron mobility and light harvesting; ②avoid the recombination | 222 |
| PbS | | PbS + m-TiO ₂ | 5.04 | ①Enlarge the grain size of CsPbBr ₃ perovskite film; | 223 |
| | | PbS + TiO ₂ | 14.95 | ②suppress the activation of intrinsic trap sites of m-TiO ₂ Downshift the conduction band of TiO ₂ , promote the driving force of an electron injection | 227 |
| Cu-Zn-In-S-Se (CZISSe) | | CZISSe + mp-TiO ₂ + CsPbBr ₃ | 5.37 | ①Enhance charge extraction; | 225 |
| Ho ³⁺ -Yb ³⁺ -F ⁻ tri-doped TiO ₂ | | Ho ³⁺ -Yb ³⁺ -F ⁻ tri-doped TiO ₂ + TiO ₂ | 9.91 ± 0.3 | ②reduce charge recombination Convert NIR light to green light | 232 |
| Gd _{1.54} Er _{0.46} (MoO ₄) ₃ (GMO:Er) | | GMO:Er + TiO ₂ | 3.41 | Convert NIR light to the visible region (near 550 nm) | 233 |
| β-NaYF ₄ :Yb ³⁺ /Er ³⁺ /Sc ³⁺ @NaYF ₄ | | β-NaYF ₄ :Yb ³⁺ /Er ³⁺ /Sc ³⁺ @NaYF ₄ + TiO ₂ | 20.19 | Convert NIR to red and green light | 243 |
| SrAl ₂ O ₄ :Eu ³⁺ | | SrAl ₂ O ₄ :Eu ³⁺ + TiO ₂ | 4.64 | Elevation of the Fermi energy level of TiO ₂ , improves light harvesting | 245 |
| ZnS/Te | Bottom HTL | ZnS/Te + PEDOT:PSS | 2.31 | Reduce series resistance, increase shunt resistance, improve mobility | 230 |
| NaCsWO ₃ @NaYF ₄ @NaYF ₄ :Yb,Er | Top HTL | NaCsWO ₃ @NaYF ₄ @NaYF ₄ :Yb,Er + spiro | 18.28 ± 0.34 | ①Widen the perovskite spectral response range; ②increase the light reflection; ③ prolong the light path, and light absorption | 231 |
| NaLuF ₄ :Yb,Er@NaLuF ₄ | | NaLuF ₄ :Yb,Er@NaLuF ₄ + PTAA | 15.86 | Convert NIR light to visible light, scatter light | 237 |
| Li(Gd,Y)F ₄ :Yb,Er | Active layer | Li(Gd,Y)F ₄ :Yb,Er + spiro-MeOTAD | 18.34 | Convert NIR to visible light | 242 |
| SnO ₂ | | SnO ₂ + P3HT-PCBM | 3.39 | Reduce the recombination | 224 |
| Fe-doped SnO ₂ | | Fe-doped SnO ₂ + P3HT | 3.04 | Extension of photogenerated exciton lifetime, overcome the burn-in regime faster | 247 |
| NaYF ₄ :Yb,Er/NaYF ₄ | | NaYF ₄ :Yb,Er/NaYF ₄ + N719 | 9.15 | Convert NIR light to visible light (450–700 nm) | 235 |
| TiO ₂ :Sm ³⁺ | | TiO ₂ :Sm ³⁺ + P25 + N719 | 5.31 | Convert UV to visible light | 244 |
| SnS | | SnS + MAPbI ₃ | 14.26 | ①Provide more nucleation sites for the growth of perovskite grains; ② accelerate carrier transfer and reduce the recombination | 226 |
| NaYF ₄ :Yb/Er | | NaYF ₄ :Yb,Er + MAPbI ₃ | 17.8 | Broaden the solar spectral use to NIR light, minimize the non-absorption energy loss | 236 |
| IR-806-β-NaYF ₄ :Yb,Er | | IR-806-β-NaYF ₄ :Yb,Er + MAPbI ₃ Er ³⁺ -Yb ³⁺ doped Zn | 17.49 | Convert NIR light (800–1000 nm) to visible emissions | 238 |
| Ho ³⁺ -Yb ³⁺ -Li ⁺ -doped TiO ₂ | | Ho ³⁺ -Yb ³⁺ -Li ⁺ -doped TiO ₂ + FAMAPbBrI ₃ | 16.88 ± 0.5 | Convert NIR to visible light, improve electron injection efficiency, and decrease recombination | 240 |
| β-NaYF ₄ :Yb ³⁺ ,Tm ³⁺ @TiO ₂ | | β-NaYF ₄ :Yb ³⁺ ,Tm ³⁺ @TiO ₂ + MAPbI ₃ | 16.27 | Convert NIR to visible light, serve as the light scatter centers | 241 |

4.1 Active layer quality improvement and carrier transfer accelerator

The performance of solar cells largely depends on the quality of the active layer, such as the purity of Si for Si solar cells and the composition of perovskite for PSCs. For example, defects unavoidably exist at the surface of perovskite thin film during

the low-temperature fabrication process, and reducing defects is a very useful way to improve the performance of PSC.²⁵⁴ This subsection discusses NCs as outstanding additives in the active layer for boosting its quality and carrier transfer acceleration.

SnO₂-Sb₂O₃ NCs were used to modify TiO₂ nanorod arrays for electron mobility improvement and electron transport



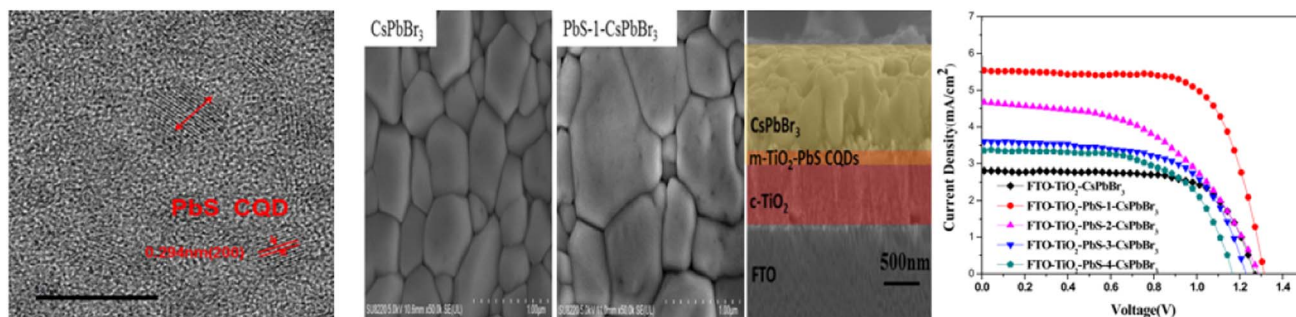


Fig. 12 Top-view and cross-section images of CsPbBr₃ film decorated with PbS NCs, and J–V curves of all-inorganic PSCs based on different TiO₂/PbS photoanodes. Adapted with permission.²⁴³ Copyright 2019, American Chemical Society.

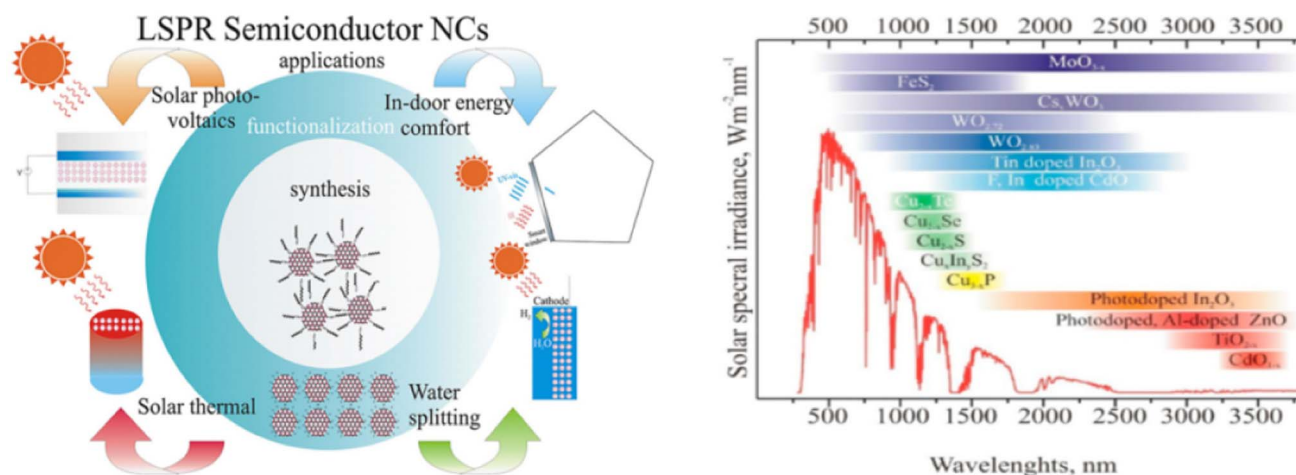


Fig. 13 Schematic of the applications of LSPR semiconductor NCs; the solar spectrum and its relevancy for energy-targeted applications of LSPR semiconductor NCs via their tunable plasmon absorbance. Adapted with permission.²⁵⁵ Copyright 2021, Elsevier.

resistance reduction. This NCs modified ETL enhanced the PCE of CH₃NH₃PbI_{3-x}Cl_x PSC from 6.5% to 7.7%.²²² PbS NCs suppress the activation of the intrinsic trap sites, provide nucleation sites to enlarge the grain size, and suppress the charge combination in CsPbBr₃ PSCs (Fig. 12).²²³ Adding SnO₂ NCs of size around 5 nm into the active layer of P3HT:PC₆₁BM made electrons more easily pass through the active layer and accelerate the electron transfer, improving the PCE of OSC from 2.67% to 3.39%.²²⁴ S₂O₃²⁻-capped Cu–Zn–In–S–Se NCs with ~5 nm size was introduced in the perovskite precursor of PbBr₂ solution to boost 22.6% enhancement of the PCE of inorganic Cs-based PSCs, which was due to promoted crystallization of CsPbBr₃ and hole extraction.²²⁵ SnS NCs with an average size of 6.9 nm were implanted into the active layer of carbon-based HTL-free mesoporous PSCs, and the device gained a high PCE of 14.26% with a 12.42% improvement. This improvement was demonstrated by more nucleation sites for the growth of perovskite grains and the accelerated carrier transfer.²²⁶ PbS NCs doped TiO₂ nanotubes (TNTs) modified the electronic and optical properties by downshifting the conduction band of TiO₂ ETL from –4.22 to –4.58 eV and promoting the driving force of an electron injection to the conductive electrode.²²⁷

4.2 Plasmonic Effect

Semiconductor NCs have exhibited localized surface plasmon resonances (LSPR), and this plasmonic effect has been used in many fields, such as solar photovoltaics, in-door energy comfort, water splitting, and so on (Fig. 13). Compared with traditional LSPR materials (noble metals), the semiconductor LSPR NCs allow a wide range of wavelength tunability from visible towards near-infrared (NIR) and further to mid-IR, leading to larger absorption of solar light. Higher absorption of the active layer in solar cells increases the current intensity and thus, the device performance. DSSCs based on plasmonic effect by ZnO or SnO₂ and TiO₂/SnO₂ have been investigated.²⁵⁴ From Fig. 13, it can be seen that different oxides, sulfides, and selenides such as MoO_{3-x}, Cs_xWO₃, TiO_{2-x}, CdO_{1-x}, doped In₂O₃, doped ZnO, Cu_{2-x}S, Cu_xIn_yS₂, Cu_{2-x}Se, *etc.* broaden the response spectra from 500 nm to nearly 3800 nm. Effective light harvesting due to the plasmonic effect shows great potential in solar cell application. Given the limited self-absorption bands of solar cells, the above oxide and sulfide NCs can be applied as additives to widen the light harvesting range. Clearly, this will reduce energy loss and raise the device performance in a considerable way.





Fig. 14 Solar spectrum, absorption and emission spectrum of up-conversion nanocrystals and EQE curve of γ -CsPbI₃ PSC, J - V curves of PSCs based on different nanocrystals, and statistical PCE distribution histograms of 30 devices, schematic energy diagram for Yb³⁺ and Er³⁺. Adapted with permission.²³⁷ Copyright 2019, American Chemical Society.

4.3 Light conversion

As discussed in Section 3, light conversion is an efficient way to boost the PCE and stability of solar cells. Based on this point, NC light-converting layers were investigated in the previous part. It is also true that light conversion can be realized by NC additives, which will be summarized in this part.

4.3.1 Up-conversion. Rare-earth (RE) elements are famous for light up-conversion and further application in solar cells. RE element-doped semiconductor NCs have been added as additives in active layers and charge transport layers for high-performance DSSCs and PSCs. NIR lights were up-converted to visible lights and thus elevated the device PCE due to wider solar radiation absorption (Fig. 14). The RE element-based NCs, which can be used in up-converting materials as additives in solar cells, mainly contain Yb, Er, Ho, and Sc doped materials like Ho–Yb–F doped TiO₂, Er–Yb doped ZnO₂, Ho–Yb doped Gd₂O₃, Yb–Er doped NaYF₄ and Yb–Er doped Li(Gd,Y)F₄. As shown in Fig. 14, the schematic energy diagram for Yb³⁺ and Er³⁺ are suitable for up-conversion and the related solar cells gain high efficiency. The up-conversion NCs can be added in the active layer, ETL, and HTL in different solar cells like OSC, DSSC, and PSC. The original active layers cannot absorb the whole range of sunlight and thus result in energy loss. After assembling NCs with up-conversion ability, the non-responsive long-wavelength range of sunlight will be converted to shorter wavelengths and absorbed by active layers to re-generate hole-electron pairs. This strategy can enhance the utilization of the infrared range of sunlight and the performance of solar cells.

4.3.2 Down-conversion and down-shifting. Down-conversion and down-shifting NCs are advantageous for high-performance solar cells due to the efficient utilization of UV lights. Typical Sm³⁺-based TiO₂NCs were used in DSSCs and obvious improvement of PCE was gained (Fig. 15) through

converting ultraviolet to visible light. Better performance of solar cells was obtained by means of down-converting NCs such as ZnS:Er in Si-based devices and CeO₂:Gd in OSC.^{249,250} The shortest wavelength response by perovskite is about 400 nm.²⁵⁶ The energy of sunlight with wavelengths shorter than 400 nm will be wasted. Furthermore, the UV lights can damage the perovskite or organic active layer and reduce the device stability. So, the PCE and light stability of solar cells can be increased by using down-conversion or down-shifting NCs.

4.4 Light scattering and reflection

Light scattering and reflection are well-known for boosting the optical absorption of different solar cells. TiO₂:Zn NCs can scatter light and promote the performance of conventional DSSCs.²⁵⁷ Due to the ultralow (<1%) photoluminescence quantum yield, NaLuF₄:Yb,Er@NaLuF₄NCs acted as scattering centers and extended the sunlight optical path by combining scattering and reflecting sunlight.²³⁷ NaYF₄:Yb³⁺,Tm³⁺ NCs serve as scatter centers to enhance light harvesting for PSCs.²⁴¹ We can conclude that NCs are good at light absorption enhancement due to light scattering and reflecting, and this is an available approach for improving the device performance.

4.5 Heat sinks

Except for optical management, heat control is also important for solar cell operation because elevated temperatures may increase energy loss and destroy the devices. In the traditional photovoltaic/thermal (PV/T) system, the temperature of thermal energy is always limited by the operation temperature of PV cells. The oleylamine solution of Cu₉S₅NCs was adopted in the spectral splitting filter to harvest the moderate-temperature heat. After successful thermal energy collection, the maximum



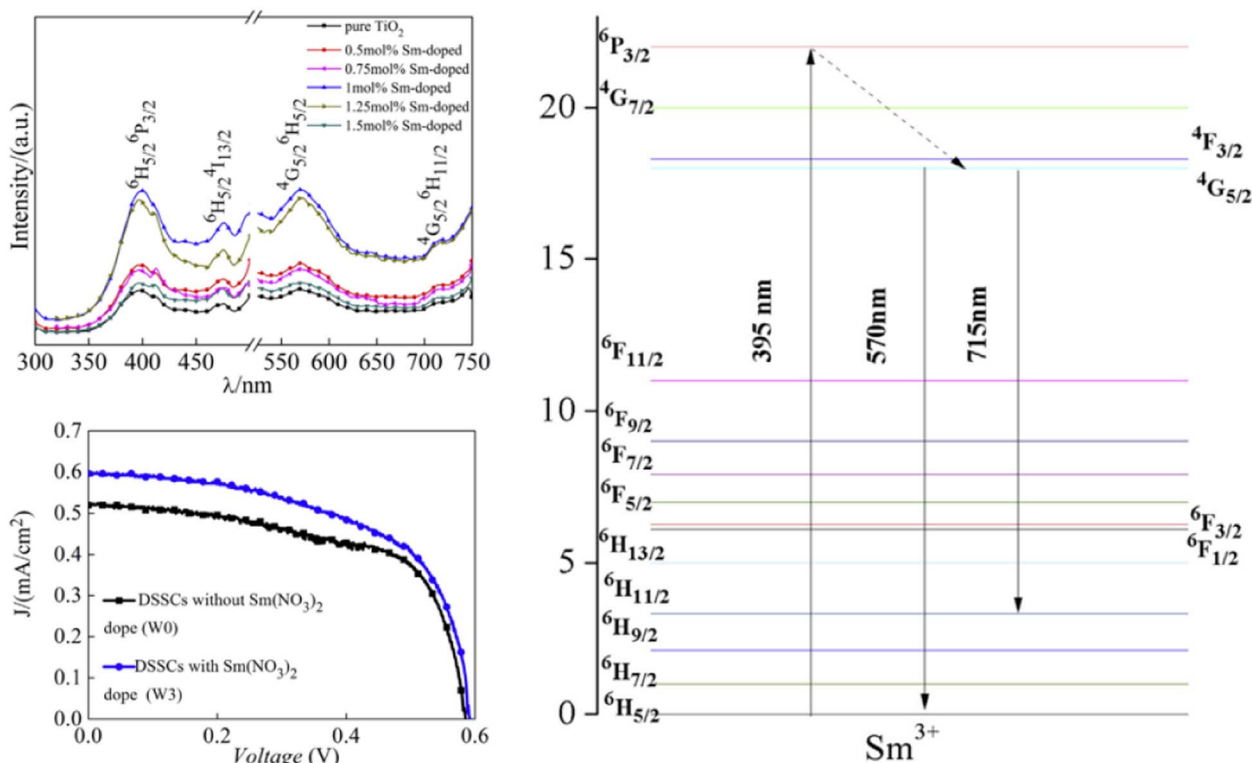


Fig. 15 Excitation spectrum ($\lambda_{em} = 567$ nm) and emission spectrum ($\lambda_{ex} = 395$ nm) of $\text{TiO}_2:\text{Sm}^{3+}$ NCs with different Sm^{3+} doping concentrations, and schematic energy-level diagrams to show the details of down-conversion mechanisms *via* excitation using 395 nm radiation for $\text{TiO}_2:\text{Sm}^{3+}$ NCs. Adapted with permission.²⁴⁴ Copyright 2016, Elsevier.

overall efficiency of the present PV/T collector is 34.2%, with a 17.9% improvement.²⁵⁸ In a concentrator photovoltaic nanocrystal-phase change material (PCM) hybrid system, Al_2O_3 , CuO , and SiO_2 were used to save energy and offer safe operating conditions. Compared with pure PCM (0 wt%), Al_2O_3 -PCM at 5 wt% increased the thermal conductivity, and the melting rate reduced the solar cell temperature. The electrical efficiency was improved from 6.36% to 8% and gained temperature uniformity from 20 °C to 12 °C. This strategy would be recommended for residential and industrial applications in solar cells.²⁵⁹

4.6 Other functions

ZnTe NCs with an average of 2.96 nm in the active layer demonstrated increased photo-generation and improved efficiency by reduced series resistance and improved mobility.²³⁰ Fe-doped SnO_2 NCs incorporated into the active layer of P3HT:PCBM improved the J_{sc} of OSC due to the extension of photogenerated exciton lifetime as a result of the magnetic field. Meanwhile, these NC-reinforced devices showed the tendency to overcome the burn-in regime faster and indicated the diluted magnetic semiconductor NCs had the potential to increase the stability of the devices.²⁴⁷

5. Summary and outlook

In recent years, NCs as functional layers and additives have been widely used in solar cells, significantly enhancing their

performance. Here, we summarize NCs-based HTL, ETL, IFL, and additives for solar cells. NCs can boost the device performance in many ways, such as increasing the charge transport ability, suppressing charge recombination, broadening light harvest, and so on.

Based on previous investigations, we propose some promising strategies to enhance the performance of solar cells by using NCs.

(I) Optical management. Full spectrum absorption under low-cost conditions: both up-converting and down-shifting materials. For down-shifting, doped NCs with large Stokes shift, such as Mn or Cu doped NCs, have great potential due to no self-absorption, facile synthesis, and low cost. Cu^+ , Ag^+ doped n-type metal oxide NCs,²⁶⁰ $\text{Fe}_{1-x}\text{S}_2$ NCs,²⁶¹ and In doped Cu_xS NCs,²⁶² with great potential for spectra broadening are also suggested for high-performance solar cells. $\text{CaMoO}_4:\text{Er}^{3+}, \text{Yb}^{3+}$ NCs would offer great potential for conserving energy in Si solar cells.²⁶³ Certainly, the photoluminescence efficiency of NCs is very important when they are used to convert light in solar cells. Excellent optical management of solar cells can utilize more sunlight and improve the device performance.

(II) Electronic optimization. The charge transfer ability is mainly determined by the electronic properties of charge transport materials. The performance of solar cells can be improved by electronic optimization. One approach is a component change of materials such as n doping for n-type NCs and p doping for p-type NCs. Finding more suitable dopants for NCs will further boost the PCE and stability of solar



cells. Meanwhile, the size and ligand control of NCs are also considered to optimize their electronic properties and fabricate better-performance solar cells.

(III) Interface engineering. Interfacial layers between different functional layers show different functions in solar cells. In further developments, more NCs IFL will be used to improve device performance by preventing direct contact between the active layer and charge transport layer, impeding the entry of water and oxygen, and protecting and destroying the active layer with UV lights.²⁶⁴ So, NC IFL, with good photo-electronic properties, can adjust energy alignment, accelerate charge transport, enhance light harvest, and protect the active layer.

(IV) Cross utilization. The metal-organic framework (MOF) materials can improve the efficiency and stability of solar cells due to their unique properties.²⁶⁵ NCs with small sizes can be considered to mix with MOF and enhance the performance of devices. In addition, NCs can be utilized as light harvesters, HTL, ETL, and IFL, so we suggest their application in all-NC solar cells.

Conflicts of interest

The authors declare no conflict of interest.

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