Inorganic top electron transport layer for high performance inverted perovskite solar cells

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Abstract
As promising photovoltaic devices, perovskite solar cells (PSCs) have attracted extensive and ongoing attention due to easy manufacturing and high power conversion efficiency (PCE). Although the PCE is lower than that of PSCs with normal structure, inverted PSCs have been widely investigated due to their lower hysteresis and potential application. Electron transport layer (ETL) on top of perovskite film in inverted PSCs plays a significant role in device performance. Inorganic top ETL has been used to replace organic ETL for their excellent characters. This review summarizes the progress of inorganic top ETL for high-performance inverted PSCs. Firstly, the principles of top ETL and advantages of inorganic ETL are highlighted. Then the established top ETLs are summarized. Subsequently, various strategies for top ETL fabrication are shown to demonstrate their advantages and shortcomings. Finally, conclusion and outlook of top ETL in inverted PSCs are presented, addressing the issues and directing the hopeful solutions.

KEYWORDS
high performance, inorganic, perovskite solar cell, top electron transport layer

1 | INTRODUCTION

In recent years, perovskite solar cells (PSCs) have gained worldwide attention from the lab to industry fabrication and PSC with a power conversion efficiency (PCE) greater than 25% has been reported.1 Compared with the champion PCE of normal PSCs, this value of inverted PSCs is certified as 22.3%.2 Although the PCE value is some lower, inverted PSCs have some special advantages, such as much lower hysteresis and promising application...
on tandem solar cells, which makes them a famous star among the new-generation photovoltaic devices.\textsuperscript{3–5} As an important functional layer in high performance inverted PSC, electron transport layer on top of perovskite film (namely top ETL) play an irreplaceable role. Known to be a star ETL, fullerene and its derivative such as [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) has been widely used in inverted PSCs, exhibiting negligible hysteresis.\textsuperscript{6–10} However, difference between the Fermi level of PCBM and the work function of Ag electrode often results in Schottky barrier at their interface,\textsuperscript{11} leading to charge carrier recombination and high series resistance ($R_S$) and thus low PSC performance. To address these issues, inorganic top ETLs have been used due to their advantages such as good optical and electrical properties, low cost, facile synthesis, controllable properties, and so forth.

In this review, we first summarize the principles of top ETLs and the advantages of inorganic materials as top ETLs. Then the reported top ETLs and their fabrication/modification methods are presented. Finally, the conclusion and outlook are shown, containing some potential alternatives as inorganic top ETL for inverted PSCs.

## 2 | TOP ETL FOR INVERTED PEROVSKITE SOLAR CELLS

Planar PSCs (shown in Figure 1) are generally divided into n-i-p (regular) and p-i-n (inverted) types, which are respectively with the structure of transparent conductive oxide (ITO or FTO)/ETL/perovskite/HTL/rear electrode (Ag, Al, or Au) and transparent conductive oxide (ITO or FTO)/HTL/perovskite/ETL/rear electrode (Ag, Al, or Au). The PSCs work as the following steps: (a) the active layer (perovskite) absorbs photons under sun illumination; (b) photo-generated carriers emerge and separate into holes and electrons; (c) holes and electrons respectively transport to electrodes through HTL and ETL; (d) current engenders in the external circuit. Inverted PSCs have been widely studied for nearly 10 years and the first one with a low efficiency value of 3.9% was proposed in 2013 with the structure of ITO/poly(3,4-ethylenedioxythiophene):poly(styrene-sulfonate) (PEDOT:PSS)/CH$_3$NH$_3$PbI$_3$ (MAPbI$_3$)/1-(2-methoxycarbonyl)-propyl-1-phenyl-(6,6)-C$_{61}$ (PCBM)/bathocuproine (BCP)/aluminum (Al).\textsuperscript{12} Up to present, the champion PCE of inverted PSC is 22.3% (certified)\textsuperscript{13} for a small area and 18% for large area of 19.276 cm$^2$.\textsuperscript{14} Meanwhile, a mini-module of 36 cm$^2$ area with p-i-n structure first passed the 85°C/85% RH test according to the standards of IEC 61215 in 2019,\textsuperscript{15} indicating that inverted PSCs may be more suitable for commercialization.

### 2.1 | Principles of top ETL

Through the development of inverted PSCs, it is known to us that ETL atop the perovskite layer plays critical role both in device PCE and stability. The principles of top ETL in inverted PSCs are shown in Figure 2 and described as follows:

1. **Facile fabrication**, such as solution process, low-temperature even no annealing, and so forth. One advantage of PSCs is solution process.\textsuperscript{16} To lower the fabrication difficulty of PSCs, solution process for ETL is needed. Additionally, annealing is used to remove the solvent left after the above solution process. However, high annealing temperature will destroy the underneath perovskite layer. Therefore, low-temperature annealing or no annealing can prevent the destruction of perovskite from high temperature, thus pledging high device performance.

2. **Suitable energy level**: Mismatching energy level in PSCs will result in non-radiative recombination at the interfaces and inefficient charge transport from perovskite to ETL and rear electrode, causing thermal potential loss and mainly reducing the open circuit voltage ($V_{OC}$) and fill factor (FF) of the devices.\textsuperscript{17–21} So, suitable energy level of ETL, both the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO), is critical to device performance. High quality top ETL with suitable energy level is beneficial to electron transporting and hole blocking.

3. **High electrical conductivity**: Electron transporting in both n-i-p and p-i-n PSCs affects the device performance. Higher electrical conductivity leads smaller $R_S$. 

![Figure 1: Structure of (A) n-i-p type PSC and (B) p-i-n type PSC](image1)

![Figure 2: Schematic diagram of the principles of top ETL](image2)
of PSC, which brings in higher short-circuit current ($J_{SC}$), higher FF, and lower hysteresis thus higher device performance.12–26

4. Interfaces: From the working mechanism of inverted PSCs, we know that the electron–hole pairs are generated under sunlight soaking and separated into free carriers at the interface.16 Generally, there are two ETL-based interfaces in inverted PSCs, concluding interfaces of perovskite/ETL and ETL/rear electrode. Interfacial defects from the interface of perovskite/ETL will improve the possibility of non-radiative recombination, which lowers the device performance.27–30 Meanwhile, the difference of work function (WF) between the ETL and rear electrode would form a Schottky barrier at the interface of ETL/rear electrode, leading to inefficient electron transport and lower device performance.31–35 Additionally, interface modification can improve device performance through a better energy alignment, reduced recombination, trap passivation, excellent contact with other functional layers, and lower hysteresis.36–40 The interfaces affect the performance of inverted PSCs and interface engineering is an efficient strategy for performance improvement.

5. Morphology: The morphology of top ETL also influences the device performance. Excellent morphology of top ETL will result in good contact between perovskite and ETL, which increases electron extraction and transport and inhibits recombination.28,41–48 ETL on top of perovskite layer has another function to avert the contact of perovskite and rear electrode. The penetration of perovskite through ETL to metal electrode degrades the electrode and decrease the device performance.29,50 Homogeneous ETL can efficiently prevent direct contact between the perovskite and rear electrode and greatly reduce device shunting and current leakage, enhancing device performance.28,42,51–65 In addition, good morphology of ETL, such as smooth and full coverage, is beneficial for the deposition of rear electrode and facilitates the formation of ohmic contact between the ETL and rear electrode.66–71

6. Stability: PSCs performance will decrease along with the operational time due to water, oxygen, light, and heat. As known to us, efficient encapsulating can resist water and oxygen and thus ensure the corresponding stability. Photo- and thermal-stability of inverted PSCs are mainly affected by the functional layers of charge transport layers (CTLs, concluding ETL, and hole transport layer [HTL]),72–91 perovskite layer,92–117 and rear electrode.16,118–142 Top ETL is an irreplaceable layer for high performance inverted PSC and inevitably resolve the device stability.3,6,29,34,42,45,63,65,71,81,143–175 Therefore, high stability of top ETL will enhance the stability of PSCs and promote the device commercialization.

7. Low cost. Known to all, one of the issues that impede the commercialization of PSCs is fabrication cost. Top ETL is responsible for a great part of the whole cost of inverted PSCs. High cost of fullerene derivatives, such as PCBM and its modification, is an obstacle to commercializing inverted PSCs.25,145,176–181 Low cost of top ETL fabrication is beneficial for the PSC commercialization.30,34,180,182–193

2.2 Advantages of inorganic top ETL

Organic materials have been widely used as top ETL in efficient inverted PSCs.25 The most popular organic top ETMs are fullerenes ($C_{60}$ and $C_{70}$) and their soluble form phenyl-C61-butyric acid methyl ester (PCBM) due to their low-temperature deposition process and efficient electron transporting.25,34,51,194–199 Among them, PCBM was used as ETL in most p-i-n PSC cases.7–10,200,201 However, there are some shortcoming for fullerene different electron transport materials (ETMs), such as narrow range of LUMO level, relatively poor morphological stability, and high cost of synthesis and purification.199

As shown above, some intrinsic weak points exactly exist in organic top ETL. Many researchers have continuously worked on finding inorganic alternatives to boost higher PCE and stability with lower cost. Compared with organic top ETL, inorganic top ETL has the advantages of (a) facile fabrication process,30,64,168,202–205 (b) high intrinsic stability,3,4,18,32,50,206–209 (c) easily adjustable optical and electronic properties,3,28,34,35,42,153,159,208 (d) low-temperature or no post-treatment26,41,50,155,168,190,203 (e) low cost,68,163,187,210,211 (f) additional function as passive layer.7,36,175 All the advantages of inorganic top ETL accelerate its application in high-performance inverted PSCs.

To verify the excellent properties of inorganic top ETL, some characterizations should be done. Transmittance, absorption spectra, mobility, conductivity et al. are used to demonstrate the optical and electronic properties. Surface defect passivation due to top ETL can be analyzed through the change of defect density. Many other characterizations not mentioned here are also used to illustrate the improved properties of inorganic ETL.

2.3 Established inorganic top ETL

Inorganic top ETL for inverted PSCs has gained wide attentions due to above advantages. Metal oxides and their modified derivatives (such as doping with other elements and mixed with other materials)
<table>
<thead>
<tr>
<th>Architecture</th>
<th>PCE (%)</th>
<th>Stability</th>
<th>Hysteresis (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Organic-</strong></td>
<td><strong>FTO/PEDOT:PSS/PCBM/TiOx/Al</strong></td>
<td>9.8</td>
<td>NM</td>
<td>194</td>
</tr>
<tr>
<td><strong>inorganic</strong></td>
<td><strong>ITO/GO/PCBM/ZnO/Al</strong></td>
<td>12.40</td>
<td>NM</td>
<td>20</td>
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<td><strong>multilayer</strong></td>
<td><strong>ITO/PEDOT:PSS/PCBM/Polymer/ZnO/Al</strong></td>
<td>8.15</td>
<td>NM</td>
<td>212</td>
</tr>
<tr>
<td><strong>ETLs</strong></td>
<td><strong>FTO/NiOx/PCBM/TiOx/Ag</strong></td>
<td>20.65</td>
<td>① &gt; 85% after 500 h, continuous light illumination ① &gt; 98% after 500 h, at 85°C</td>
<td>214</td>
</tr>
<tr>
<td><strong>ITO/PEDOT:PSS/PCBM/PEN/Ag</strong></td>
<td>14.5</td>
<td>&gt;50% after 120 h, continuous light soaking at ~50% RH, unencapsulated</td>
<td>Free</td>
<td>27</td>
</tr>
<tr>
<td><strong>ITO/PEDOT:PSS/PCBM/di-PDI + DMBI/TiO2/Al</strong></td>
<td>10.0</td>
<td>NM</td>
<td>NM</td>
<td>218</td>
</tr>
<tr>
<td><strong>FTO/NiMgLiOx/PCBM/Ti(Nb)Ox/Ag</strong></td>
<td>20.65</td>
<td>① &gt; 85% after 500 h, continuous light soaking (429 nm UV cut off) under ambient condition, encapsulated ② &gt; 90% after 500 h, encapsulated in dark at 85°C</td>
<td>144</td>
<td></td>
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<tr>
<td><strong>ITO/P3CT-K/CuZnS/PCBM/ZnO/Al</strong></td>
<td>18.30</td>
<td>89% after 72 h</td>
<td>3.83</td>
<td>149</td>
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<td><strong>ITO/PTAA/PCBM/C60/Ag</strong></td>
<td>18.38</td>
<td>NM</td>
<td>NM</td>
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<td><strong>ITO/PEDOT:PSS/PCBM/Br-PDI/ZnO NP/Ag</strong></td>
<td>10.50</td>
<td>NM</td>
<td>NM</td>
<td>214</td>
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<tr>
<td><strong>ITO/NiO/PCBM/BCP/Cr/CrO3/Au</strong></td>
<td>18.5</td>
<td>After 1000 h, AM 1.5G, at 70–75°C</td>
<td>NM</td>
<td>156</td>
</tr>
<tr>
<td><strong>ITO/CuI/PEDOT:PSS/PCBM/C61BM/ZnO/Al</strong></td>
<td>14.3</td>
<td>88% after 720 h, unencapsulated in glovebox</td>
<td>NM</td>
<td>150</td>
</tr>
<tr>
<td><strong>FTO/Cu@CuI/PCBM/ZnO/Ag</strong></td>
<td>18.8</td>
<td>90% after 1000 h, at RT with ~25% RH</td>
<td>NM</td>
<td>157</td>
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<tr>
<td><strong>ITO/CuI/PEDOT:PSS/PCBM/C61BM/ZnO/Al</strong></td>
<td>14.3</td>
<td>88% after 720 h, nonencapsulated in glovebox</td>
<td>NM</td>
<td>150</td>
</tr>
<tr>
<td><strong>ITO/Spiro-TTB/PCBM/LiF/C60/ALD-SnO2/IZO/Ag</strong></td>
<td>~11.3</td>
<td>90% after 1000 h, dark at 85°C with 85% RH</td>
<td>NM</td>
<td>151</td>
</tr>
<tr>
<td><strong>ITO/NiO/PCBM/LiF/PC60BM/SnO2/ZTO/ITO/LiF/Ag</strong></td>
<td>12.5</td>
<td>100% after 1000 h, at 35°C with 40% RH</td>
<td>NM</td>
<td>146</td>
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<tr>
<td><strong>TCO/NiO/PCBM/ZnO NPs/S-ALD ZnO/ITO</strong></td>
<td>14.7</td>
<td>96% after 1500 h, at 65°C in N2</td>
<td>Negligible</td>
<td>152</td>
</tr>
<tr>
<td><strong>ITO/NiOx/PCBM/c-Nb2O5(001)/PC61BM/Bphen/Ag</strong></td>
<td>11.74</td>
<td>80% after 400 h, in N2-filled glovebox at 85°C</td>
<td>137</td>
<td></td>
</tr>
<tr>
<td><strong>ITO/PEDOT:PSS/PCBM/AZO/SnO2/Ag/SnOx</strong></td>
<td>11.5</td>
<td>① 100% after 4500 h, in N2 at 60°C</td>
<td>2.61</td>
<td>147</td>
</tr>
<tr>
<td><strong>ITO/PEDOT:PSS/PCBM/AZO/SnO2/Ag</strong></td>
<td>12.7</td>
<td>① ~90% after 1000 h, at 25°C with 60% RH ② ~100% after 3000 h, in N2-filled glovebox at 60°C</td>
<td>Negligible</td>
<td>153</td>
</tr>
<tr>
<td>Architecture</td>
<td>PCE (%)</td>
<td>Stability</td>
<td>Hysteresis (%)</td>
<td>Reference</td>
</tr>
<tr>
<td>--------------------------------------------------</td>
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</tr>
</tbody>
</table>
| ITO/PEDOT:PSS/PVK/PCBM/AZO/SnOx/Ag               | 12.8    | ① 100% after 350 h, at 23°C with 50% RH  
② ~100% after 1032 h, in N2-filled glovebox at 60°C | 0.55           | 148       |
| FTO/NiO/PVK/PCBM/BCP/AZO/Ag                     | 18.45   | 86.7% after 500 h, continuous 1 sun illumination at 85°C with 20%–60% RH | 1.76           | 60        |
| FTO/NiO3/PVK/BaSnO3/PCBM/Ag                     | 16.2    | 92% after 30 days, nonencapsulated at ~20°C with ~30% RH                  | NM             | 46        |
| ITO/NiOx/PVK/PCBM/ZnSnO2/Ag                     | 17.76   | ~90% after 14 days, with 30% RH                                           | NM             | 143       |
| FTO/CuNiOx/PVK/PC61BM/CeOx/Ag                   | 17.35   | 90% after 1000 min, continuous illumination                               | Negligible     | 29        |
| FTO/NiMgLiO/PVK/PCBM/CeO3/Ag                    | 18.7    | ① 100% after 200 h, in N2-filled glovebox  
② 91% after 200 h, under continuous light soaking with ~30% RH | 0.64           | 34        |
| ITO/PTAA/MAPlx/Pc61BM/ZnO NPs/Al                | 17.2    | NM                                                                        | NM             | 215       |
| FTO/NiO/PVK/PCBM/ZnO/Al                         | 17.75   | NM                                                                        | NM             | 2         |
| ITO/PEDOT:PSS/PVK/ZnO-PCBM/Ag                   | 6.08    | 67% after 20 days, encapsulated, RT with 30% RH                           | 2.14           | 3         |
| ITO/NiOx/PVK/PCBM/AZO/Ag                        | 13.6    | NM                                                                        | NM             | 5         |
| ITO/NiOx/PVK/PCBM/SnO2/Ag                       | 18.77   | NM                                                                        | Negligible     | 207       |
| ITO/PEDOT:PSS/PVK/PC[70]BM/AZO/Al                | 13.3    | Over 90% after 170 h, exposure                                           | Negligible     | 42        |
| ITO/NiO/PVK/PC60BM/AZO/TPPO/Ag                  | 19.2    | 80% after 800 h, constant illumination                                    | NM             | 6         |
| ITO/NiO3/PVK/PCBM/Nb-TiO2/BCP/Ag                | 20.7    | 100% after 1000 h, 1 sun continuous illumination at open-circuit conditions in N2 at 35°C | 0.49           | 71        |
| ITO/PEDOT:PSS/PVK/PC70BM/TiO2/Al                 | 14.03   | 100% after 23 days, with encapsulation in N2 glove box                   | NM             | 81        |
| FTO/NiO3/PVK/C60/SnO2-HClO4/Ag                  | 16.36   | >80% after 90 days, in air with 55% ± 10% RH                             | 4.6            | 48        |
| ITO/NiO3/PVK/PCBM/Ti(Nb)O2/Ag                   | 18.49   | 90% after 500 h, at 85°C with 85% RH                                      | Negligible     | 155       |
| ITO/NiO:BN/PVK/PCBM/ZnO/Ag                      | 20.74   | ~85% after 60 days, in air with 30%–60% RH                               | NM             | 164       |
| ITO/NiO3/PVK/Eu2O3/PC61BM/Bhen/Ag               | 14.09   | >90% after 400 h, thermal aging at 80°C                                  | NM             | 167       |
| ITO/NiO3/PVK/PCBM/CeO3/Ag                       | 17.47   | 85% after 300 h, at 30°C with 50% RH                                     | 4.92           | 168       |

(Continues)
<table>
<thead>
<tr>
<th>Architecture</th>
<th>PCE (%)</th>
<th>Stability</th>
<th>Hysteresis (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITO/NiOx/PVK/PCBM/ZnO/Ag</td>
<td>17.23</td>
<td>⊕ &gt;87% after 4500 h, unencapsulated, in N₂</td>
<td>0.5</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td></td>
<td>⊕ &gt;82% after 200 h, encapsulated, at 85°C with 85% RH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FTO/NiOx/PVK/C₆₀/SnO₂-HClO₄/Ag</td>
<td>16.36</td>
<td>&gt;80% after 90 days, in air with 55% ± 10% RH</td>
<td>4.6</td>
<td>48</td>
</tr>
<tr>
<td>ITO/PEDOT:PSS/GO:PEG/PVK/PCBM/MoS₂/Ag</td>
<td>19.14</td>
<td>NM</td>
<td>NM</td>
<td>225</td>
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<tr>
<td>ITO/CuI/PVK/PCBM/AZO/Ag</td>
<td>~14.21</td>
<td>~90% after 15 days, at ~35°C with ~50% RH</td>
<td>NM</td>
<td>170</td>
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<tr>
<td>ITO/PTAA/WS₂/PVK/C₆₀/ZnSe/Cu(Ag)</td>
<td>20.92</td>
<td>78% after 40 days, at 25°C with ~30% RH</td>
<td>1.43</td>
<td>171</td>
</tr>
<tr>
<td>ITO/PEDOT:PSS/PVK/PVK//PC₆₁BM/ZnMgO/Al</td>
<td>15.61</td>
<td>~90% after 20 day, in glove box</td>
<td>0.45</td>
<td>129</td>
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<tr>
<td>ITO/PEDOT:PSS/WSe₂/PVK/PCBM/ZnO/Ag</td>
<td>16.2</td>
<td>29% after 30 days, Unencapsulated at 25°C with 30%–40% RH</td>
<td>NM</td>
<td>216</td>
</tr>
<tr>
<td>ITO/PEDOT:PSS/PVK/CdSe/ZnS/C₆₀/BCP/Ag</td>
<td>20.00</td>
<td>75% after 2400 h</td>
<td>NM</td>
<td>172</td>
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<tr>
<td>ITO/NiOx/PVK/ZnO NPs/C₆₀/Ag</td>
<td>15.60</td>
<td>85% after 350 h, continuous light soaking in N₂</td>
<td>NM</td>
<td>173</td>
</tr>
<tr>
<td>FTO/Mo/Sb₂Se₃/PVK/C₆₀/GZO/Ag</td>
<td>16.8</td>
<td>NM</td>
<td>NM</td>
<td>222</td>
</tr>
<tr>
<td>FTO/MoSe₂/PVK/PMMA/C₆₀/AZO/Ag</td>
<td>18.0</td>
<td>NM</td>
<td>NM</td>
<td>223</td>
</tr>
<tr>
<td>ITO/NiOx NP/PVK/PCBM/ZnO NP/Al</td>
<td>18.6</td>
<td>⊕ 87% after 1000 h, continuous light soaking(with UV filter) at 35°C in N₂</td>
<td>NM</td>
<td>213</td>
</tr>
<tr>
<td></td>
<td></td>
<td>⊕ &gt; 80% after &gt;1000 h, at 100°C</td>
<td></td>
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<tr>
<td>ITO/PVK/C₆₀/SnO₂/ITO</td>
<td>14.2</td>
<td>⊕ 95% after 1000 h, unencapsulated in air in the dark at 85°C</td>
<td>NM</td>
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<tr>
<td></td>
<td></td>
<td>⊕ 97% after 1000 h, encapsulated at 85°C with 85% RH</td>
<td></td>
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<tr>
<td>ITO/NiOx/PVK/PC₆₁BM/SnO₂/Ag</td>
<td>19.7</td>
<td>NM</td>
<td>2.03</td>
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<tr>
<td>Organic–inorganic hybrid ETL</td>
<td></td>
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<tr>
<td>FTO/NiOx/PVK/ZnO@C₆₀/Ag</td>
<td>13.3</td>
<td>80% after 360 h, unencapsulated at 85°C</td>
<td>NM</td>
<td>61</td>
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<tr>
<td>FTO/NiOx/PVK/C₆₀:Co-TiO₂/Ag</td>
<td>22.13</td>
<td>⊕ 50% after 110 h, continuous one-sun illumination in ambient air ⊕ 97% after 70 days, 20%–87% RH</td>
<td>2.5</td>
<td>159</td>
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<tr>
<td>ITO/NiOx/PVK/TiO₂/PCBM:C₆₀/Ag</td>
<td>20.5</td>
<td>⊕ ~90% after 350 h, continuous light soaking at 30°C with 50 ± 5% RH ⊕ ~98.5% after 16 months, at 30°C with 50% ± 5% RH</td>
<td>1.95</td>
<td>64</td>
</tr>
<tr>
<td>Architecture</td>
<td>PCE (%)</td>
<td>Stability</td>
<td>Hysteresis (%)</td>
<td>Reference</td>
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<tr>
<td>--------------------------------------------------</td>
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<td>----------------</td>
<td>-----------</td>
</tr>
<tr>
<td>FTO/NiO/PVK/ALD Al2O3/PCBM/PPDIN6/Ag</td>
<td>20.40</td>
<td>95.3% after 150 days, unencapsulated in dry N2 glove box</td>
<td>Negligible</td>
<td>175</td>
</tr>
<tr>
<td>ITO/NiO/PVK/PCBM-SnS2/ZnO/Ag</td>
<td>19.95</td>
<td>80% after 50 days, in ambient atmosphere</td>
<td>14.27</td>
<td>226</td>
</tr>
<tr>
<td>ITO/PEDOT:PSS/PVK/PC61BM/ZnO@PFBC/Al</td>
<td>16.93</td>
<td>80% after 200 h, heating at 85°C in N2</td>
<td>NM</td>
<td>65</td>
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<tr>
<td>FTO/NiOx/PVK/ZnO@C60/Ag</td>
<td>12.60</td>
<td>&gt;90% after 10 h, unencapsulated under the stabilized power output operation</td>
<td>NM</td>
<td>174</td>
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<tr>
<td>ITO/PEDOT:PSS/PVK/PCBM/BCP:ZnO NPs/Ag</td>
<td>15.50</td>
<td>NM</td>
<td>NM</td>
<td>217</td>
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<tr>
<td>ITO/NiO/PVK/PC60BM/Phen-NaDPO:Sn(SCN)2/Ag</td>
<td>18.2</td>
<td>100% after 80 h, in dark (O2 and H2 ≤ 10 ppm)</td>
<td>0</td>
<td>227</td>
</tr>
<tr>
<td>ITO/PEDOT:PSS/-PVK/Phen-NaDPO:Sn(SCN)2/Ag</td>
<td>18.2</td>
<td>NM</td>
<td>NM</td>
<td>227</td>
</tr>
<tr>
<td>ITO/CuInS2/PVK/PCBM/TiO2/Ag</td>
<td>14.1</td>
<td>NM</td>
<td>3.55</td>
<td>126</td>
</tr>
<tr>
<td>FTO/NiO/GO/PVK/GO-Li/TiO2/Al</td>
<td>11.2</td>
<td>70% after 12 days, in a dry box in the dark 28%-32% RH</td>
<td>Negligible</td>
<td>31</td>
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<tr>
<td>ITO/PEDOT:PSS/PVK/CdSe QDs/LiF/Ag</td>
<td>14.2</td>
<td>NM</td>
<td>NM</td>
<td>177</td>
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<tr>
<td>ITO/c-NiOx/mp-NiOx/PVK/Zn(In)O/Al</td>
<td>16.2</td>
<td>&gt;85% after 460 h, continuous light soaking at 30°C with 20–30% RH, encapsulated</td>
<td>3.2</td>
<td>145</td>
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<tr>
<td>FTO/MoS2/PVK/TiO2/Ag</td>
<td>20.43</td>
<td>NM</td>
<td>NM</td>
<td>210</td>
</tr>
<tr>
<td>FTO/NiMgLiO/PVK/c-Nb:TiO2/Sb</td>
<td>14.8</td>
<td>⊠ &gt; 95% after 1000 h, dark at 85°C in N2</td>
<td>3.2</td>
<td>158</td>
</tr>
<tr>
<td></td>
<td></td>
<td>⊠ &gt; 90% after 1000 h, under 1 sun in N2 at 60°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FTO/NiMgLiO/PVK/c-TiO2/Bi/Ag</td>
<td>13.85</td>
<td>95% after 1000 h, encapsulated under 1 sun in N2 at 45°C</td>
<td>NM</td>
<td>62</td>
</tr>
<tr>
<td>ITO/NiO/PVK/Bi2S3/Au</td>
<td>13.1</td>
<td>&gt;80% after 30 days, unencapsulated at 25°C with 50%-75% RH</td>
<td>6.11</td>
<td>50</td>
</tr>
<tr>
<td>ITO/NiOx/PVK/ZnO/Al</td>
<td>16.1</td>
<td>&gt;90% after 60 days, 25°C with 30%-50% RH</td>
<td>NM</td>
<td>72</td>
</tr>
<tr>
<td>FTO/NiOx/PVK/SnO2/Al</td>
<td>13.5 ± 1.8</td>
<td>NM</td>
<td>NM</td>
<td>4</td>
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<tr>
<td>FTO/KFeO2/PVK/ZnO/Pt</td>
<td>10.83</td>
<td>85% after 10 days, ambient environment at 30°C with 40%-45% RH</td>
<td>NM</td>
<td>163</td>
</tr>
</tbody>
</table>

(Continues)
are mainly used as inorganic top ETL. Among them, -
ZnO, ZnO, 2,3,20,61,65,72,126,149,150,152,157,160
–165,169,173,211 TiOX, 31,62,64,81,144,159,166,194,210,218and SnOX
1,48,148,151,153,207,219 are the most popular choices. In addition, Al, In and Ga
doped ZnO are also promising for electron transporting in
inverted PSCs. 5,6,42,60,121,147,148,153,170,220
–223 The reported inorganic materials used as ETM are summarized in Table 1.

### 2.3.1 Binary metal oxides and their modification

ZnO is a n-type semiconductor metal oxide with advan-
tages of wide bandgap (3.3 eV), high exciton binding
energy, low cost, low temperature fabrication, and high
electron mobility. These excellent properties facilitate its
application as efficient ETL in high performance inverted
PSCs and benefit to the device commercialization. You
et al. gained greatly enhanced air-stability of inverted PSC
by using ZnO as top ETL. This ZnO based device nearly
had no PCE decrease after 60 days in ambient air with
room light illumination. 72 For large-area durable flexible
PSCs, ZnO was used as top ETL to get high PCE and stabili-
ty. 211 Recently, ZnO nanoparticles (NPs) were synthesized
through a low temperature (64.7°C) process. 161 ZnO based
device gained 10.83% PCE and retained 60% of its initial
PCE after 250 h at 30°C with 40%–45% relative humid-
ity. 163 Combined with the use of inorganic Cu:NiOx HTL,
ZnO based inverted PSC showed better PCE and excellent
stability than the device based on conventional organic
transport layers (Figure 3). 169

To further improve the properties of ZnO thus the
performance of inverted PSC based on ZnO, different
modification methods have been used. For metal oxides,
doping is a conventional way to enhance their properties,
especially the electronic characteristics. Based on semi-
conductor physics, doping element with higher valence
than Zn into ZnO is beneficial for improving its elec-
tronic properties. 204 This strategy has been adopted and
doped ZnO has boosted the performance of PSCs based
on this metal oxide. Al doped ZnO (ZAO) with better
properties than pristine ZnO has been widely used as top
ETL in inverted PSCs. 5,6,42,60,121,147,148,153,170
References

<table>
<thead>
<tr>
<th>Architecture</th>
<th>PCE (%)</th>
<th>Stability</th>
<th>Hysteresis (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTO/NiOx/PVK/TiOx/Al</td>
<td>13.3</td>
<td>&gt;60% after 1050 h, uncover condition at 25°C with 45% RH</td>
<td>NM</td>
<td>166</td>
</tr>
<tr>
<td>Cu/CuI/PVK/ZnO/Ag</td>
<td>12.8</td>
<td>NM</td>
<td>NM</td>
<td>211</td>
</tr>
<tr>
<td>FTO/Mo/Cu2ZnSnSe4/PVK/ZnS/IZO/Ag</td>
<td>17.4</td>
<td>NM</td>
<td>NM</td>
<td>220</td>
</tr>
<tr>
<td>FTO/NiOx/PVK/MoOx/Au</td>
<td>5.52</td>
<td>long-term stability at high temperatures up to 160 °C</td>
<td>NM</td>
<td>45</td>
</tr>
<tr>
<td>FTO/Cu2O/PVK/SiO2/GZO/Ag</td>
<td>18.4</td>
<td>NM</td>
<td>NM</td>
<td>221</td>
</tr>
<tr>
<td>FTO/Cu:NiOx/PVK/ZnO/Ag</td>
<td>16.51</td>
<td>90% after 6 months, unencapsulated under ambient conditions</td>
<td>0.18</td>
<td>169</td>
</tr>
<tr>
<td>ITO/NiOx/PVK/CeOx/Ag</td>
<td>5.60</td>
<td>90% after 500 h, Unencapsulated in an atmospheric condition at 40–45°C with 45%–50% RH</td>
<td>NM</td>
<td>63</td>
</tr>
<tr>
<td>ITO/NiOx/PVK/Sn:In2O3/In2O3/Ag</td>
<td>20.65</td>
<td>①91.9% after 69 day, under 85°C ②91.8% after 2000 h, 12 h continuous 1 sun illumination and then 12 h interval in the dark</td>
<td>0.7</td>
<td>203</td>
</tr>
</tbody>
</table>

Abbreviations: AZO, Al doped ZnO; BN, boron nitride; CZTS, Cu2ZnSnS4; GO, graphene oxide; GZO, Ga doped ZnO; IZO, In doped ZnO; NM, not mentioned; NP, nanoparticle; PVK, perovskite; RH, relative humidity; RT, room temperature.
TiO$_x$, nearly the original inorganic ETL used in n-i-p PSCs, has also been utilized for efficient electron transport in inverted PSCs.\textsuperscript{31,62,64,81,144,166,194,218} More suitable energy level and higher conductivity of C-TiO$_2$ than C-In$_2$O$_3$, C-In$_2$O$_3$, C-SnO$_2$, and C-ZnO facilitated is as an excellent top ETL than the other four oxides (shown in Figure 5A,B). Ultrasmall 4 nm TiO$_2$ nanocrystals were synthesized and used as top ETL in inverted PSCs by Choy et al. and ~ 20% PCE, high shelf-life stability, and reproducibility were gained. TiO$_2$ also shows high transmittance like ZnO, and excellent electronic properties. According to the UV–vis absorption in Figure 5E, after coating TiO$_2$ on perovskite layer, nearly no light loss were observed. The device stability was greatly enhanced by comparing with the organic ETL based device.

As the same as ZnO, the properties of TiO$_x$ can be adjusted by doping.\textsuperscript{204} As shown in Figure 6A, Nb doped TiO$_2$ boosted higher PCE and reduced hysteresis.\textsuperscript{158} Additional electron in Nb$^{5+}$ compared with Ti$^{4+}$ enabled higher electron mobility.\textsuperscript{71} The enhanced properties made the ETL more conductive and the inverted PSC with higher PCE due to higher Jsc (Figure 6). Doping of transition metal Co and Fe tuned the electronic

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**Figure 3** Diagram for charge transfer between perovskite layer, ETL, and rear electrode in inverted PSCs

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**Figure 4**

(A) Transmittance spectra of AZO layers with different thickness fabricated on quartz substrates, 150 nm (blue filled squares), 250 (green open circles), and 390 nm (red open triangles). (B) Current density versus voltage characteristics of two compared devices ITO/PEDOT:PSS/CH$_3$NH$_3$Pb(I$_{1-x}$Cl$_x$)$_3$/PC[70]BM/Al (black filled squares) and ITO/PEDOT:PSS/CH$_3$NH$_3$Pb(I$_{1-x}$Cl$_x$)$_3$/PC[70]BM/AZO/Al (red open circles) under dark conditions. (C) Current density versus voltage characteristics of two compared devices ITO/PEDOT:PSS/CH$_3$NH$_3$Pb(I$_{1-x}$Cl$_x$)$_3$/PC[70]BM/Al (black filled squares) and ITO/PEDOT:PSS/CH$_3$NH$_3$Pb(I$_{1-x}$Cl$_x$)$_3$/PC[70]BM/AZO/Al (red open circles) under illumination. (D) Distribution of the PCE represented in histograms as obtained from 20 pixels in two separated experimental runs.

*Source: A–D reproduced with permission: Copyright 2016, Wiley-VCH*\textsuperscript{42}
FIGURE 5  (A) UPS and (B) conductivity measurements for different carbide-metal oxide ETLs. (C) TEM image and the corresponding diffraction pattern of TiO$_2$ nanocrystals. (D) Corresponding energy band diagram of TiO$_2$-fullerene-based PSCs. (E) UV–vis absorption spectra before and after TiOx deposition. (F) Normalized efficiency of devices with TiOx ETL and C$_{60}$/BCP ETL shelf-aged in uncovered and ambient conditions over 1000 h, taken from eight devices over four substrates for each ETL.

FIGURE 6  (A) J-V curves of PSCs with C-TiO2 and Nb-doped C-TiO2 ETLs. (B) Transient photocurrent measurements. (C) External quantum efficiency. (D) J-V curves from champion perovskite devices employing a PTAA HTL both with and without the interfacial bilayer. (E) The electrical conductivity was measured from devices of FTO/ETL/Al at different temperatures. (F) J-V curves of inverted PSCs using different ETLs. (G) Stability test under continuous one-sun Xe lamp illumination in ambient air, measured by tracking the current at MMP of an unencapsulated device for 120 h. (H) Device shelf life measurement by testing the J-V curve every day for over two months. Realtime relative humidity is also included.

properties of TiO\textsubscript{2} brookite nanorod (NR).\textsuperscript{159} Co and Fe doped TiO\textsubscript{2} NR improved film uniformity, electron extraction and transferability, energy level matching with perovskite, and moisture resistance. Finally, the inverted PSCs based on Co or Fe TiO\textsubscript{2} NR was boosted to higher PCE and stability, which are shown in Figure 6.

Inverted PSC based on a SnO\textsubscript{x} layer with an optimized thickness of 60 nm as efficient top ETL achieved a 19.7\% PCE value.\textsuperscript{219} This pinhole-free and conformal SnO\textsubscript{x} layer directly grown on perovskite was minimal structural damage to the underlying perovskite layer and enhanced the performance of PSC (Figure 7). The PSC performance has been found to be better than the organic ETL based devices.\textsuperscript{1,4,48,147,148,207,219} This means that SnO\textsubscript{x} is also an efficient top ETL.

Besides the common binary metal oxides of ZnO, TiO\textsubscript{x}, and SnO, other metal oxides, such as CrO\textsubscript{3},\textsuperscript{156} CeO\textsubscript{x},\textsuperscript{29,34,63,154,168} Nb\textsubscript{2}O\textsubscript{5},\textsuperscript{137} Eu\textsubscript{2}O\textsubscript{3},\textsuperscript{167} MoO\textsubscript{3},\textsuperscript{45} In\textsubscript{2}O\textsubscript{3},\textsuperscript{205} SiO\textsubscript{2},\textsuperscript{221} and Al\textsubscript{2}O\textsubscript{3},\textsuperscript{75} VO\textsubscript{x}\textsuperscript{229} have been used as top ETL in efficient inverted PSCs. From the SCLC plots in Figure 8 A and B, we can see that CeO\textsubscript{x} based device has lower trap density than PCBM based device, suggesting better properties of inorganic metal oxide than organic PCBM. Furthermore, the stability of CeO\textsubscript{x} based PSCs shown much higher stability than PCBM based devices under different conditions.

Besides doping strategy discussed above, some other ways to modify the binary metal oxide top ETL have been adopted. One efficient approach is using organic material to form hybrid or bilayer ETL. This can improve the electron transport ability and thus the performance of inverted PSCs.

### 2.3.2 Ternary metal oxide

Because of extraordinary optical and electrical properties, some ternary metal oxides,\textsuperscript{205} like Zn(In)O\textsubscript{4},\textsuperscript{145} Ti(Nb)O\textsubscript{4},\textsuperscript{155} BaSnO\textsubscript{3},\textsuperscript{46} Zn\textsubscript{2}SnO\textsubscript{4},\textsuperscript{143} and ZnMgO,\textsuperscript{129} have been used as top ETL in inverted PSCs. Compared with pure PCBM, the ternary metal oxides block the erosion of humidity and ion migration from the perovskite to Ag electrode more efficiently. This reveals the PSCs with high stability in both ambient and humidity conditions.

Compared with binary metal oxides, ternary metal oxides may have better stability due to their chemical structure, boosting the PSCs to higher stability. Additionally, the synthesis of ternary metal oxides is not complicated than binary metal oxides. Both the better stability and facile synthesis suggest that ternary metal oxides are excellent alternatives as efficient top ETL for inverted PSCs (Figure 9).

### 2.3.3 Other inorganic top ETL

Besides metal oxides, metal chalcogenides have also been applied as top ETL in inverted PSCs and boosted high device performance. Bi\textsubscript{2}S\textsubscript{3},\textsuperscript{50} ZnS,\textsuperscript{172,220} CdSe,\textsuperscript{172,177} ZnSe,\textsuperscript{171,224} CdS,\textsuperscript{228} MoS\textsubscript{2},\textsuperscript{228} SnS,\textsuperscript{226} Sn(SCN)\textsubscript{2},\textsuperscript{227} have been applied in high performance inverted PSCs. As the same as ZnO, other II-VI semiconductor metal sulfides and selenides have good optical and electrical characters. The fabrication of metal chalcogenide top ETL are similar to metal oxide ones without more post-treatments. In addition, they also have good chemical stability. These original properties make them as suitable alternatives to metal oxides as top ETL in inverted PSCs.

The main parameters of electronic properties of reported inorganic ETLs are summarized in Table 2. It can be seen that these inorganic ETLs have good properties, concluding suitable energy level matching with perovskite, high electron mobility, and conductivity. The above advantages are beneficial for efficient electron extraction and transporting.

### 3 FABRICATION AND MODIFICATION OF INORGANIC TOP ETL

To obtain inorganic top ETL with excellent properties through facile fabrication is essential to PSC performance.
and its commercialization. In some cases, only pristine metal oxide does not show the optimal state as top ETL. So various modifications have been done to pristine metal oxides to improve their properties for efficient inverted PSCs. We review the fabrication and modification of inorganic top ETL in this section.
3.1 Fabrication

The top ETL fabrication process is an important step during the whole procedure of inverted PSC preparation. Different from n-i-p PSCs, ETL of inverted PSCs should experience relatively low temperature (commonly <110 °C) because high temperature will damage the perovskite film under ETL. Therefore, low-temperature or no post-treatment will prevent the perovskite from thermal degradation. Additionally, facile fabrication strategy can save cost and boost the commercialization of PSCs. The main fabricating methods to gain top ETL with high quality are as follows.

3.1.1 Spin-coating of pre-synthesized nanoparticles

The most used method of top ETL forming is presynthesis and a following spin-coating. Inorganic ETMs for inverted PSCs are mostly synthesized through solvothermal method. In Figure 10 A, a typical synthesis of ZnO NPs is shown. This solvothermal method may bring in some insulated ligands such as oleic acid. Ligand exchange is needed before the spin-coating on perovskite film. After this exchange shown in Figure 10 B,C, ETM solution are dropped on the perovskite layer and then form as ETL by spin-coating shown in Figure 10D. To avoid the ligand exchange, solvent without long carbon chain can be used for NP synthesis. The adoption of a new solvent such as water or ethanol simplifies the fabrication process of NPs before spin-coating. Furthermore, the reaction temperature using oleic acid is higher than that of water and ethanol, suggesting low-cost procedure. The thickness of ETL formed by spin-coating can be controlled through the concentration of ETL solution, spin time, spin speed and circles. Equally important, the synthesis and ligand exchange also affect the properties of top ETL and thus the performance of the inverted PSCs.

3.1.2 Atomic layer deposition

To passivate perovskite surfaces, a promising way of atomic layer deposition (ALD) had been applied to form metal oxide. Another strong point of ALD is that it is a scalable vapor-phase thin-film deposition strategy to gain highly uniform layer on rough perovskite surface with precisely controllable thickness and prominent reproducibility. The properties of metal oxide from by ALD can be changed with different temperature. Considering the drawback of classical ALD, spatial ALD was introduced to deposit efficient metal oxide in efficient inverted PSC. The schematic of the spatial ALD for top ETL is shown in Figure 11 A. This process can be finished under low temperature (80 °C), protecting the perovskite film below.

3.1.3 Direct annealing strategy

Similar with the popular method to fabrication of ETL in n-i-p PSCs, top ETL for inverted PSCs can also be formed by annealing the precursor solutions. The process is shown in Figure 11B, suggesting a typical procedure of this strategy. Some things must be paid attention as follows: (a) low temperature below 110 °C to prevent the perovskite from thermal damage, (b) appropriate metal precursor to void insulated residue during low-temperature annealing.
3.1.4 | Chemical vapor deposition

Another alternative for growing metal oxide layer on perovskite film is atmospheric pressure chemical vapor deposition (AP-CVD). The illustration is shown as Figure 11C,D. We can see that the oxide is grown by a soft chemical-based way, which is unlike sputter-deposition. Furthermore, the growth rates are very high and no vacuum is required, which is unlike ALD and thermal evaporation and saves fabrication cost.

3.1.5 | Sputtering

Metal oxides can also be deposited on perovskite layer by magnetron sputtering. High energy ions bombardment during sputter can bring in low roughness of metal oxide layer, which induces good electric contact with the perovskite film. Similar with CVD method, the thickness of top ETL can be precisely controlled and the optimized value will gain for efficient PSC.

3.1.6 | Thermal evaporation

For inorganic materials as Bi₂S₃, it can be deposited by simple thermal evaporation, which is controlled by tuning the current of a tungsten filament. This method has the same advantage as sputtering, well controlling the thickness of top ETL. Some more inorganic top ETL can be gained by this efficient method and used in high-performance inverted PSCs.

4 | SUMMARY AND OUTLOOK

Considering the shortcomings of organic ETLs, we surveyed and analyzed inorganic top ETL for efficient inverted PSCs in this review. From the reported inorganic top ETLs, we sum up their advantages compared with organic ETLs, which concludes facile fabrication, high electron conductivity, tunable energy level, high stability,
adjustable properties, and low cost. Although many inorganic materials have been used for efficient electron transporting in inverted PSCs, there is still much room to be deeply probed for further enhancement of ETL properties thus the performance of inverted PSCs. In the near future, efforts are anticipated to be thrown into, but not limited to, the following directions:

A. Finding more new inorganic ETLs for efficient inverted PSCs. Previous inorganic ETLs mainly focus on binary metal oxides, narrowing the range of materials choosing. Multiple metal oxides, metal sulphide, and selenides with homologous properties can expand the inorganic ETL family and boost the PSC performance.

B. Exploring facile fabrication strategy. To simplify the procedure of device preparation, facile fabrication strategy of top ETL is beneficial to scalable deposition of top ETLs, which is promising for the commercialization of PSCs.

C. Improving the properties of inorganic ETLs. As known, ETL is an very important functional layer in
inverted PSCs. Improved properties of ETL is a direct and useful way to enhance device performance.

In summary, these efforts above will boost the PSC performance and the real application of the devices.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

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REFERENCES


45. Liu C, Li WZ, Fan JD, Mai YH, Schropp REI. Ultra-thin MoOx as cathode buffer layer for the improvement of all-inorganic CsPbBr3 perovskite solar cells. Nano Energy. 2017;41:75-83.


106. Wang JT, Meng FX, Li RX, et al. Boosting efficiency and stability of planar inverted (FAPbI3)0.85(MAPbBr3)0.15 solar cells via FAPbI3 and MAPbBr3 crystal powders. Sol RRL. 2020;4:2000091.


127. Shin SH, Shin DH, Choi S-H. Enhancement of stability of inverted flexible perovskite solar cells by employing...


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