Review

Advances in hole transport materials engineering for stable and efficient perovskite solar cells

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1. Introduction

Organic–inorganic halide perovskites have attracted worldwide attention due to their impressive electrical and optical properties leading to remarkable performance in solar cells and light emitting devices \cite{1–5}. These materials can be represented by a general formula ABX\textsubscript{3}, where A is an organic methylammonium (CH\textsubscript{3}NH\textsubscript{3}) ion \cite{6} or formamidinium (NH=CHNH\textsubscript{3}) ion \cite{7–9}, B is Pb, Sn, Cs, or Cd ion, and X can be a halogen ion, I\textsuperscript{–}, Br\textsuperscript{–}, or Cl\textsuperscript{–} \cite{10}. The remarkable performance of these perovskites in solar cells is attributed to their broad light absorption throughout the visible and near infrared spectrum, low exciton binding energy (~2 meV), and direct band gap \cite{11}. In addition to high absorption coefficients, these materials demonstrated (i) long carrier lifetime (~270 ns) resulting in diffusion lengths of few microns (~1 µm in its thin films \cite{12} and up to ~175 µm in single crystals \cite{13}) so that the carriers can be transported safely across a 300-nm thick perovskite absorber without recombination \cite{12,14–17}, (ii) high dielectric constant (~18−70) \cite{11,18}, and (iii) high charge carrier mobility (~10–2320 cm\textsuperscript{2} V\textsuperscript{−1} s\textsuperscript{−1}) \cite{16,19} thereby making them ideal photovoltaic materials \cite{16,18,20}. Owing to these unique characteristics, a certified power conversion efficiency (PCE) of 22.1% is reported so far \cite{21,22}.

Fig. 1 gives a broad overview of the various configurations of PSCs. In a typical device, PSCs employ a thin perovskite absorber layer (~300 nm) between an electron transport layer (ETL) and a HTM. Based on whether electrons or holes are collected at the bottom conducting substrate (usually a transparent conducting oxide, TCO), the PSCs are classified as n-i-p or p-i-n device, respectively. The former is also often termed as conventional and the latter as inverted architectures in the literature, depending on whether an ETL or HTM is deposited over the TCO (Fig. 1). The n-i-p architecture can be further divided into (i) mesoporous PSC, employing a metal oxide semiconductor (MOS) layer (~200–600 nm thick) as ETL with an additional n-type compact layer (CL) over it \cite{4}, (ii) meso-super-