

## Perovskite solar cells

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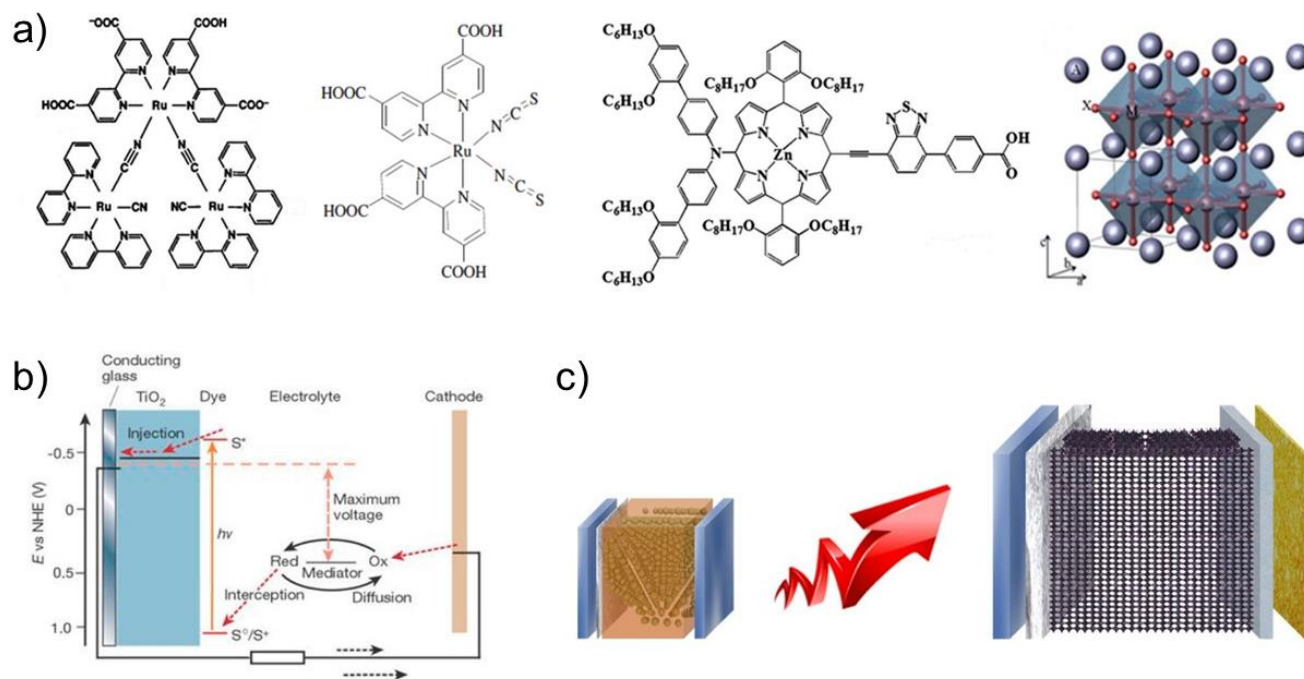
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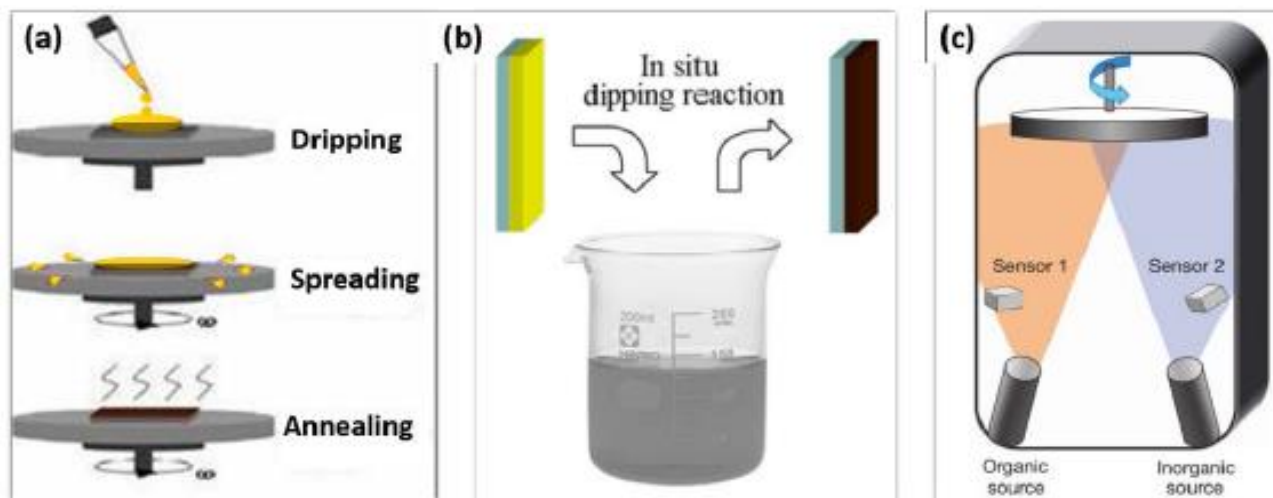
Presently, over 85% of world energy requirements are satisfied by finite fossil fuels, which are inexpensive but with the concealed cost of detrimental consequences on health and environment<sup>1</sup>. On the other hand, solar power is infinite. Therefore, photovoltaic technologies are ideal to supply green and grid-free energy. The first generation silicon solar cells yield 25.6% laboratory efficiency, and 15 to 20% module efficiency depending on the manufacturer<sup>2</sup>. The second generation of thin-film technologies based on microcrystalline silicon, CdTe, and CIGS (copper indium gallium selenide) yields power conversion efficiency over 12 to 15%<sup>2</sup>. The third generation, based on dye-sensitized solar cells (DSC) and organic solar cells, has an efficiency in the range of 10 to 12%<sup>3</sup>. In the DSC, the functionalized sensitizers, shown in Figure 1a, anchors onto TiO<sub>2</sub> nanoparticles, and absorbs visible light to form excitons. At the interface between the sensitizer and the TiO<sub>2</sub> nanoparticles, excitons split into charges that are then collected at the electrodes. Modification of the light-absorbing sensitizer from a trinuclear<sup>4</sup> to a mononuclear ruthenium dye increased power conversion efficiency from 7% to 11%<sup>5</sup>. A molecularly engineered donor–chromophore–acceptor porphyrin-based sensitizer produced power conversion efficiency over 13%<sup>6</sup>. The three landmark sensitizers and the operating mechanism of the DSC are shown in Figures 1a and 1b, respectively. The DSC reported is based on a liquid electrolyte with iodine/iodide and cobalt

redox mediators. The liquid electrolyte may be replaced by an organic or inorganic hole transporting material to form solid-state DSCs. The power conversion efficiency of the solid-state DSC is half of the liquid DSC due to issues with the infiltration of the hole transporting material caused by the pore size of the TiO<sub>2</sub>.

Perovskite solar cells are considered to be the most promising photovoltaic technology because of their favorable power conversion efficiency of 22%, addressing the increasing energy demand, greenhouse gasses, and depleting fossil fuels<sup>7</sup>. The Perovskite solar cell (PSC) configuration is similar to the solid-state DSC where the sensitizer is replaced by the perovskite pigment<sup>7</sup>. The Perovskite, named after the Russian mineralogist L.A. Perovski, has a specific crystal structure with the ABX<sub>3</sub> formula. Where A is the organic cation situated at the eight corners of the unit cell, B is the metal cation located at the body center, and X represents the halide anion in the six face centers (see *Figure 1*)<sup>8</sup>. The perovskite ABX<sub>3</sub> materials have significant advantages compared to other photovoltaic materials such as inexpensive precursors, high absorption coefficient, ambipolar charge transport properties, long carrier diffusion lengths, extremely low exciton binding energy. The band gap tunability by substituting "A" cations and "X" halides from I<sup>-</sup> to Cl<sup>-</sup>, and simple fabrication methods such as one step, sequential deposition and dual source sublimation as shown in *Figure 2*.



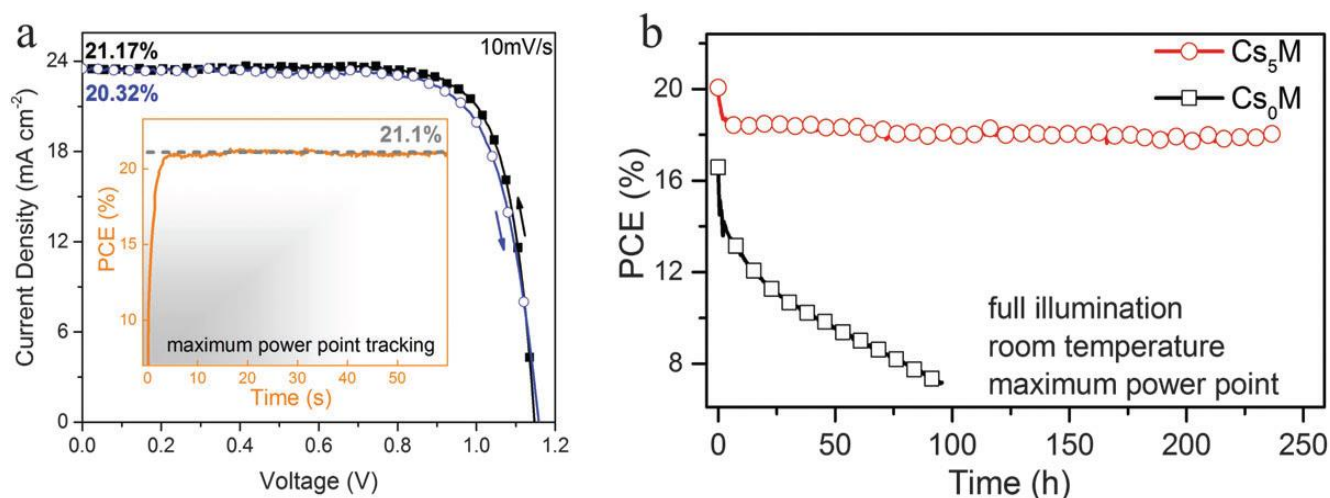
**Figure 1.** a) Chemical structures of landmark sensitizers and cubic perovskite of general formula,  $ABX_3$ ; b) working principle of dye-sensitized solar cells (DSC); c) Now and then, showing an evolution of Perovskite solar cell (PSC) from DSC.



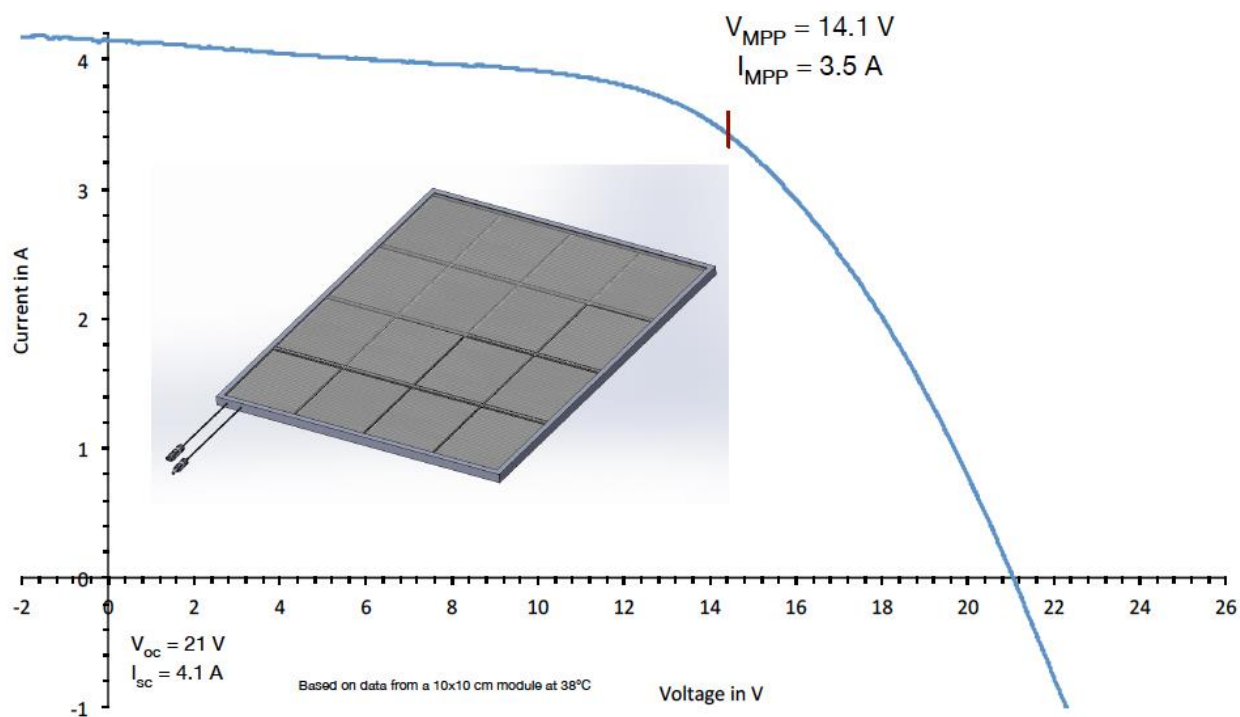
**Figure 2.** Three general methods for deposition of active perovskite layer. (a) one step, (b) sequential and (c) dual source sublimation.

Typical PSC configurations are n-i-p mesoscopic or planar and inverted p-i-n architecture. The configuration n-i-p devices composed of an electron transporting material TiO<sub>2</sub> (ETM), infiltrated with the perovskite absorbing material and coated with a hole transporting material (HTM), which plays an important role to facilitate the holes from perovskite to the gold as a back contact. The highest reported efficiency over 22%

is based on n-i-p structure, where the perovskite is an intrinsic semiconductor, TiO<sub>2</sub> acts as an electron acceptor material (n-type layer), and poly tertiary aryl amine polymer (PTAA) as the hole transporter (p-type layer)<sup>9-10</sup>. Such a high PCE is achieved due to the relatively large open-circuit voltage ( $V_{OC}$ ) of PSC, generally over 1.0 V, which is outstanding compared to other photovoltaic technologies such as organic- or silicon-based



**Figure 3.** (a) Current–voltage scans for the best performing Cs<sub>5</sub>M device showing PCEs exceeding 21% with little hysteresis. (b) Aging for 250 h of a high performance Cs<sub>5</sub>M and Cs<sub>0</sub>M devices in a nitrogen atmosphere held at room temperature under constant illumination and maximum power point tracking.



**Figure 4.** Solaronix large-area photovoltaic module characterization: IV characteristics of perovskite photovoltaic panel 0.85 m<sup>2</sup> measured under 1000 W/m<sup>2</sup> Sunlight. The stability data obtained at Solaronix over 8900 hours of light soaking and the projected cost will be <20 cents/Wp. The I–V plot of the perovskite panel is computed by extrapolation from a 10 × 10 cm mini-module.

solar cells. The energy loss ratio of V<sub>oc</sub> to the bandgap energy ( $E_g$ ) in PSC is lower than that of silicon solar cells; therefore the power conversion efficiency of PSC competes with the performance of silicon solar cells. The perovskite materials have a potential to reach over 25% power conversion efficiency, and the PSC is recognized

by The World Economic Forum (2016) as one of the top 10 new technologies<sup>11</sup>.

Nevertheless, the drawback of perovskite solar cells are several: i) poor material stability under heat and light soaking conditions; ii) reduced control over device operation, i.e. hysteresis in the

current-voltage characteristic, still poorly understood;<sup>12</sup> iii) material toxicity due to the presence of lead, and iv) device instability. To improve the stability, efforts in the optimization of pure CH<sub>3</sub>NH<sub>3</sub>PbI<sub>3</sub> by compositional engineering of cations, e.g., the substitution of the methyl ammonium (MA) cation by formamidinium (FA), and anions, e.g., introducing a small amount of Br, are needed. The addition of excess lead iodide has indeed induced a breakthrough in device efficiency and reproducibility. A large variety of perovskite compositions, particularly the mixed cation/mixed halide (FAPbI<sub>3</sub>)<sub>0.85</sub>(MAPbBr<sub>3</sub>)<sub>0.15</sub> have been investigated, and recent developments even include triple cation structures containing cesium, MA, and FA to enhance the stability shown in **Figure 3**. A further advance in PSCs through significant innovation steps in material science, chemistry and device technology all combined could lead to a "paradigm shift" in the near-future energy sector. Perovskite solar cell using the hole conductor free configuration where the HTM layer is replaced by carbon, which acts as a contact electrode (see **Figure 4**). The *J-V* characteristic data computed from extrapolation from 10 × 10 cm mini-module perovskite panel is shown in **Figure 4**. Since this configuration holds the promise to be at present the cheapest and the most attractive solution among the perovskite photovoltaic architectures. The future is bright for perovskite materials with a demonstrated power conversion efficiency of 22%; PSCs could lead a revolution in power generation, storage, and consumption through truly green grid-free energy.

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