

Multidimensional perovskites enhance solar cell performance

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Organic–inorganic hybrid metal halide perovskite materials have attracted much research interest over the past decade because of their unique electrical and optoelectronic properties, e.g., long diffusion length, high charge mobility, low binding energy, high absorption coefficient, and low density of trap states. The power conversion efficiency (PCE) for the perovskite solar cells (PSCs) rapidly increased from 3.8% to 25.5%^[1, 2]. However, the long-term operational stability of PSCs in the ambient condition is intrinsically poor against the humidity, heat and UV-light, which limits its further commercialization. The poor stability of PSCs originates from the increase of the vibrational motion of MA⁺ ion inside the metal halide [MX₆]⁴⁻ octahedra under the internally generated heat and long-term heat soaking^[3]. Meanwhile, the water could accelerate the decomposition of methylamine and thereby cause the irreversible degradation of perovskites when the perovskites are in the ambient environment with relatively high humidity (> 50%). Various approaches, such as compositional engineering^[4, 5], interfacial engineering^[6, 7], and solvent engineering^[8, 9] were utilized to overcome this problem.

The low dimensional (LD) perovskites, including 2D, 1D, and 0D perovskites, derive from the 3D perovskites, which are structurally cut in slices through employing hydrophobic organic ammonia^[10]. It should be noted that, the LD perovskite materials defined here, are quite different from the morphological definition of 2D nano-sheets, 1D nano-wires, and 0D nano-particles (Fig. 1(a)). In 2D perovskites, the [MX₆]⁴⁻ octahedra are connected by large organic cations in the form of layered or corrugated sheets (Fig. 1(b)). The dimensionality of perovskite will be single layer ($n = 1$), double layers ($n = 2$), triple layers ($n = 3$) or $n = \infty$, with corner/edge/face-shared octahedra. A 2D layered perovskite thin film has high orientation and moisture stability^[11]. However, PSCs with 2D perovskite active layer perform high stability but a relatively poor PCE due to anisotropic transport property and large optical bandgap, which relate to its layered structure^[12]. In 1D perovskites, [MX₆]⁴⁻ octahedra are connected in face-sharing, corner-sharing or edge-sharing chain surrounded by organic cations, and [MX₆]⁴⁻ octahedra in 0D perovskites are completely isolated by organic cation from each other. Currently, the 1D and 0D perovskite materials are widely used in luminescent devices due to their unique photophysical properties such as large Stokes shifts and broad emission.

Overall, 3D perovskite solar cells exhibited remarkably improved PCE. However, the development of more stable perovskites is required to achieve solar modules. Clearly, LD perovskites with 2D, 1D and 0D structures present superior stability than 3D perovskites. In this scenario, LD/3D hybrid perovskites might be the ideal candidates for solar cell commercialization. However, as the long chains of organic cations in LD perovskites may prevent charge transport, the efficiency of LD perovskite solar cells is still lower compared with 3D perovskite solar cells. The enhanced stability sacrifices the efficiency.

Recently, researchers have focused their study on the LD-3D heterojunction perovskite solar cells. Snaith *et al.* reported the formation of 2D–3D hybrid perovskite platelets. The interspersed 2D layered perovskites between highly orientated 3D perovskite grains suppressed non-radiative charge recombination and exhibited an average stabilized PCE of 17.5%^[21]. Li *et al.* realized 0D–3D core-shell Cs_xFA_{1-x}PbI₃-[GaAA₃]₄ ($0 < x < 1$) hybrid perovskites (Figs. 2(a)–2(c)), which remarkably enhanced the long-term stability of perovskite solar cells while remaining high efficiency by using an effective passivation^[19]. Fan *et al.* obtained a series of 1D and 1D–3D hybrid perovskite materials. The intrinsic properties of thermodynamically stable yet kinetically labile 1D materials alleviated the lattice mismatch and passivated the interface traps in heterojunction region. The 1D–3D hybrid perovskite solar cells presented self-healing capabilities and long-term thermal stability^[5]. Likewise, Liu *et al.* made a 1D PbI₂-bipyridine (BPy) (II) perovskite, which was further utilized to prepare 1D–3D PSCs. The solar cells were stable under electric field, humidity and light soaking. The good lattice-matching in 1D–3D heterojunction domains accounts for the stability (Fig. 2(d)). Importantly, the negative ion migration was restricted by blocking the migration channel and a 21.18% PCE was obtained^[17].

By hybridizing LD perovskites with 3D perovskites, the stability and PCE of solar cells can be simultaneously improved due to the passivation of grain boundaries and the minimization of the problems related to the hygroscopic nature and thermal instability of 3D perovskite materials. Using LD perovskite layers as barriers against water penetration into device certainly has potential in improving the device stability. However, improving stability often sacrifices carriers transport and device efficiency^[22]. Building charge transport channel *via* organic groups with π - π conjugate structure is vital for improving charge-transport properties in low-dimensional perovskites^[23]. Organic groups with π - π conjugate structure, e.g., quinoline, pyridine, thiophene, etc., would establish effective carrier transport tunnel between inorganic and

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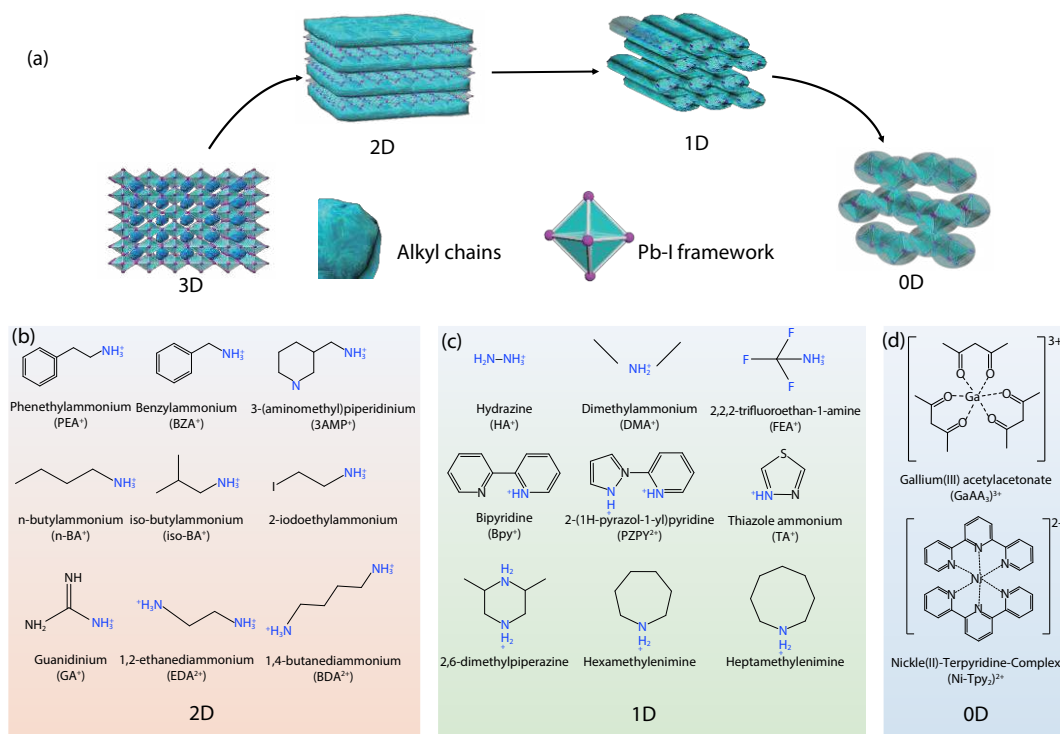


Fig. 1. (Color online) (a) The structure of hybrid lead iodide perovskite homologous semiconductors with 0D, 1D, 2D and 3D. (b–d) Chemical structure of the A-site cations reported in LD/3D perovskite solar cells^[5, 13–20].

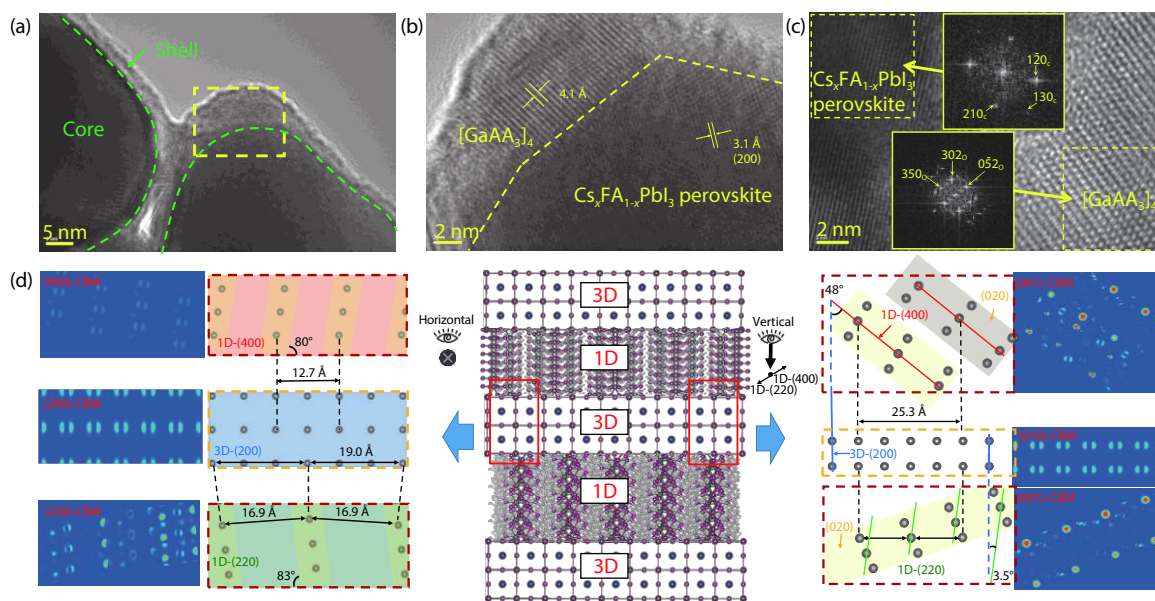


Fig. 2. (Color online) (a–c) HRTEM images of core-shell structure. Inset of the Fourier transforms of corresponding lattice fringe^[19], reproduced by permission of The Royal Society of Chemistry. (d) Schematic view of the heterojunction microstructure of 1D@3D halide perovskite. Reproduced with permission^[17], Copyright 2020, The Wiley Publishing Group.

organic domains, and between organic and organic domains, thus solving the carrier transport issue in LD-3D hybrid perovskite solar cells.

In summary, the introduction of suitable amount of LD perovskite with π - π conjugate structure can construct favorable carrier-transport channel in the heterojunction region between 3D and LD perovskites, and improve the stability of 3D perovskites. By balancing the trade-off between efficiency and stability, the LD-3D heterojunction perovskites can gift solar cells with both high efficiency and stability. The

development of multidimension-coupled perovskites will provide a new approach for developing highly efficient perovskite solar cells.

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