

# Improving the Operational Lifetime of Metal-Halide Perovskite Light-Emitting Diodes with **Dimension Control and Ligand Engineering**

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ABSTRACT: Perovskite light-emitting diodes (LEDs) have emerged as one of the most propitious candidates for next-generation lighting and displays, with the highest external quantum efficiency (EQE) of perovskite LEDs already surpassing the 20% milestone. However, the further development of perovskite LEDs primarily relies on addressing operational instability issues. This Perspective examines some of the key factors that impact the lifetime of perovskite LED devices and some representative reports on recent advancements aimed at improving the lifetime. Our analysis underscores the significance of "nano" strategies in achieving long-term stable perovskite LEDs. Significant efforts must be directed toward proper device encapsulation, perovskite material passivation, interfacial treatment to address environment-induced material instability, bias-induced phase separation, and ion migration issues.

III Metrics & More

**KEYWORDS:** perovskite, LED, lifetime, dimension control, ligand engineering

ince the initial report in 2014 on perovskite lightemitting diodes (LEDs) operating at room temperature, the development of this technology has progressed at a remarkable pace.<sup>1</sup> Following that, external quantum efficiencies (EQEs) have surpassed the 20% milestone for near-infrared,<sup>2</sup> red,<sup>3</sup> and green,<sup>4</sup> respectively. Blue perovskite LED has not achieved 20% EQE thus far due to factors such as large bandgap, unmatched injection layer energy level, and halide ion segregation.<sup>5</sup> Besides, nonradiative energy loss from triplet energy loss and defects are also limiting factors for blue perovskite LEDs.<sup>6,7</sup> Moreover, EQEs at high current injection levels, namely, high luminance/radiance levels, are still unsatisfactory for perovskite LEDs for any color due to the defects in perovskite materials.<sup>8,9</sup> According to Wang et al., the trap density in solution processed polycrystalline MAPbI<sub>3</sub> perovskite is about  $10^{16}-10^{17}$  cm<sup>-3</sup>, while in single crystals, the trap density is much lower, e.g.,  $10^9 - 10^{10}$  cm<sup>-3</sup>.<sup>10</sup> According to Qian and Guo, the defect density in GaN LEDs is around 10<sup>13</sup>-10<sup>14</sup> cm<sup>-3</sup>.<sup>11</sup> According to Zhao et al., the defect density in organic light-emitting diodes (OLEDs) is around  $10^{13}$  cm<sup>-3 12</sup> Based on these numbers, the defect density in polycrystalline perovskite is markedly higher than that of inorganic and organic LED materials. Nevertheless, it is pertinent to note that the defect density in single crystal perovskite can attain and even exceed that of both inorganic and organic analogues.

Although perovskite LEDs have achieved high EQEs, their device lifetimes still fall behind other LED technologies, such as OLEDs.  $T_{50}$ , which represents the continuous working time until the luminance drops to half of the initial value, is a common figure-of-merit used to evaluate perovskite LED lifetime. Typically, this testing is conducted with a constant driving current and an initial luminance of approximately 100 cd m<sup>-2</sup>. For mixed halide perovskite LEDs (red and blue) requiring a stable electroluminescence spectrum, the lifetime is even shorter due to phase segregation issues. Phase segregation commonly occurs in mixed-halide perovskite solar cells or LEDs when subjected to light illumination or charge-carrier injections. The occurrence described leads to the separation of the perovskite materials, causing the emergence of discrete regions characterized by different halide compositions.<sup>13,14</sup> Referring to the experience from the OLED community, some researchers evaluated the EQE and lifetime ( $T_{90}$  instead of  $T_{50}$ for OLED) at certain luminance values, such as 100, 1000, and

Article Recommendations

Dimension

Control

Lifetime Enhancement

T<sub>50</sub> T'<sub>50</sub>

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Engineering

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10 000 cd  $m^{-2}$ ,<sup>15</sup> which can make the evaluation of EQE and lifetime more standardized with a fair comparison. Regarding the operational stability of perovskite LEDs, discussions on the impact of a few critical factors are needed and elaborated below.

Water and Oxygen Induced Material Degradation. Of all the factors that lead to compromised operational stability, water and oxygen intrusions are the easiest to avoid. Note that the degradation induced by water and oxygen is a selfaccelerated process.<sup>16</sup> Proper device packaging, such as covering the active area with a coverslip and sealing the edges with ultraviolet (UV) epoxy, as well as the insertion of a buffer layer such as poly(methyl methacrylate) (PMMA) between the perovskite and above layers, can prevent vertical (out-of-plane) invasion.<sup>4,17</sup> The horizontal (in-plane) direction water and oxygen diffusion can be retarded by embedding perovskite materials in a robust nanoporous template.<sup>18</sup> Other effective procedures include using dehydrated solvents for perovskite precursor solutions, adequate baking of the sample (e.g., the most commonly used poly(3,4-ethylenedioxythiophene) polystyrenesulfonate (PEDOT:PSS)) before perovskite deposition, sublime treatment of the injection materials, etc. Moreover, the use of hydrophobic long-chain ligands such as phenethylammonium (PEA) is also beneficial.<sup>1</sup>

Joule Heating and Defects. Heat-induced material degradation is a primary issue that needs to be resolved.<sup>18,20</sup> Solution-fabricated perovskite emission layers usually have an abundance of defects that can become resistive centers, especially at high current injection conditions.<sup>21-23</sup> Perovskite film quality is highly dependent on crystal growth, posttreatments, and interfacial treatments.<sup>10</sup> By proper passivation of the defects at the perovskite crystal surfaces and inside the perovskite crystals/bulks,<sup>24,25</sup> heat-induced degradation can be relieved.<sup>26,27</sup> Perovskite LEDs typically have a maximum current density of less than 500 mA cm<sup>-2</sup>, which is significantly smaller than other devices like InGaN LEDs. Furthermore, the current density required for lasing applications, which are also electrically pumped, is typically greater than 100 A  $\text{cm}^{-2.28}$ Although high EQE is generally achieved at low current densities, studying the device behaviors at high current injection conditions (high luminance region) is more meaningful as it provides deeper understanding of EQE roll-off,<sup>29,30</sup> Auger recombination,<sup>31,32</sup> Joule heating, and so on.<sup>18,33</sup>

**Interfaces between Perovskite and Injection Layers.** The underlying injection layer affects not only the carrier injection but also the perovskite crystallization and can involve chemical reactions with the perovskite film.<sup>34</sup> Defects and vacancies at the interfaces are detrimental to the perovskite LED devices and need proper passivation.<sup>35,36</sup> For instance, by using *n*-alkylamine doping to modify the PEDOT:PSS layer, Tang et al. managed to improve the device lifetime ( $T_{50}$ , intial luminance  $L_0 = 100$  cd m<sup>-2</sup>) from 5.1 to 36.4 h.<sup>37</sup>

Impact of Metal Electrodes and Transparent Conductive Oxide (e.g., ITO) Electrodes. As the ubiquitously used PEDOT:PSS is acidic and easily absorbs moisture, it can cause corrosion problems to ITO.<sup>38</sup> Moreover, according to Dong et al., the electrochemical reactions driven by charge injections can decompose perovskite and form PbX<sub>2</sub> and deep trap states (Pb<sup>0</sup>) at anode and cathode interfaces, respectively.<sup>39</sup> Halide ions can also migrate across the injection layers and react with metal electrodes (Al, Ag, etc.) to form insulating materials (AlI<sub>3</sub>, AgI, etc.) and render black spots in the device failure regions.

Ion Migration Issue. There is now a consensus that ion migration is the most critical issue impeding the operational stability of perovskite LEDs.<sup>39,40</sup> Hitherto, there is no effective solution to completely nullify the problem of ion migration. Regardless of various strategies employed, the activation energy for ion transport in perovskite LEDs is typically less than 1 eV.<sup>41</sup> The operating voltage of the perovskite LED is much beyond the threshold which triggers ion migration. This is the substantial reason operational stability is not easy to enhance. From this perspective, high luminance perovskite LED at low working voltage can be a solution for long-time working devices. Achieving stability on par with mature InGaN LEDs and OLEDs is still a significant challenge that perovskite LEDs have yet to overcome. There is still a considerable distance to cover in terms of enhancing the stability of perovskite LEDs.<sup>42,43</sup> However, it is important not to overlook the dedicated efforts of the perovskite LED community in striving to enhance the operational stability of these devices.<sup>44,45</sup>

Some of the most common factors related to the operational stability of perovskite LEDs include those mentioned above. However, these factors are not exclusive and are often intertwined. In addition, specific studies have identified other factors that can also impact stability, such as the structure of low-dimensional perovskite. Regarding quasi-2D perovskite LEDs, Warby et al. conducted a study on the impact of ammonium cations on device stability. They found that adding phenylethylammonium bromide (PEABr), which is a commonly used alkylammonium salt, to CsPbBr<sub>3</sub> improved the EQE but decreased the device lifetime.<sup>46</sup>

Before we proceed to the detailed comparisons among the lifetimes from various reports, we present here some discussion on the lifetime  $T_{50}$ . To have a fair comparison among different reports, an initial luminance of 100 cd  $m^{-2}$  is recommended. To put this number into perspective, most cell phones nowadays have a maximum luminance of around 1000 cd  $m^{-2}$  (or 1000 nits) and brightness for common displays is around 100-150 cd m<sup>-2</sup>. Some reports use  $T_{50}$  as working time until device EQE drops to half of the initial value.<sup>34</sup> The two definitions of lifetime (by luminance and by EQE) are consistent when the testing is performed with a constant current. However, it is worth noting that perovskite LEDs often exhibit a warm-up process, characterized by an initial increase in device brightness followed by a subsequent decline after being turned on. This can cause slight differences among different reports, with some using the peak brightness as the initial value for  $T_{\rm 50}$  and others using the brightness when the device was initially turned on. The duration of the warm-up process can range from minutes to hours, further complicating the evaluation of perovskite LED lifetime,<sup>47</sup> so it is best to clearly state the starting point for calculating  $T_{50}$  in the report. In addition, constant current driving is generally considered more standard than constant voltage driving in perovskite LEDs, as the injected carrier amount is primarily determined by the current. Recently, we have seen some exciting reports showing perovskite LEDs' lifetimes longer than 10 000 h.48,49 In this Perspective, we will review selected reports on state-ofthe-art perovskite LEDs and their strategies for improving lifetime. Through these reports, we can observe the significance of "nano" strategies in enhancing the lifetime of perovskite LEDs. Broadly, these strategies can be categorized into two types: dimension control and ligand engineering, although these categories may overlap at times.





Figure 1. Surface 2D/bulk 3D heterophase perovskite LED with a  $T_{50}$  of 200 h. (a) Schematic of the LED structure. (b) Operational lifetimes of LEDs with pure 3D, surface-2D/bulk-3D, and quasi-2D perovskites. Images reprinted with permission from ref 51. Copyright 2020, Wiley-VCH.



Figure 2. Single halide quantum dot in mixed halide perovskite matrix perovskite LED with a  $T_{50}$  of 2400 h when the hole injection layer was PEDOT:PSS:PFI. (a) HRTEM image of quantum dot-in-matrix solid. (b) Relative luminance versus operation time at ambient conditions (23–25 °C; relative humidity ~ 30%), measured with a constant drive current and an initial luminance of 914 cd m<sup>-2</sup> (quantum dot-in-matrix LED) and 184 cd m<sup>-2</sup> (quantum dot-only LED). The lifetime ( $T_{50}$ ) of quantum dot-in-matrix LED at 100 cd m<sup>-2</sup> is estimated to be ~2100 h based on an acceleration factor (*n*) of 1.95. (c) Initial luminance values versus operation lifetimes ( $T_{50}$ ) measured at ambient conditions (23–25 °C; relative humidity ~ 30%). Images reprinted from ref 52. Copyright 2021, American Chemical Society.

#### DIMENSION CONTROL

One effective strategy for improving the performance and stability of perovskite LEDs is to introduce dimension control. This involves using 2D perovskite phases, shell additives, and metal oxide frameworks (MOFs) at the crystal surface/ interface to passivate defects (reducing the density of defects with passivation layer, which can fill vacancies in the perovskite lattice or remove excess halides) and block ion migration, leading to enhanced radiative recombination and longer device lifetimes. Moreover, the implementation of quantum confinement can be effectively utilized to attain blue/red radiance sans dependence on amalgamated halides, thereby enhancing color steadfastness. For instance, the mitigation of surface defects holds significant importance for perovskite nanocrystal devices due to the substantial proportion of surface area to volume in nanocrystals.<sup>50</sup> Below are a few representative works reporting the dimension control strategy.

Surface 2D/Bulk 3D Heterophase Perovskite LED (Near-Infrared,  $T_{50} = 200$  h, 2020). Han et al. utilized the surface 2D/bulk 3D heterophase perovskite emission layer (Figure 1a) to address the instability problem by reducing surface/interface defect states.<sup>51</sup> The surface was immune to ion migration; meanwhile, the spatial and potential confine-

ment enabled fast radiative recombination. The formamidinium (FA) perovskite could be formed into 3D, surface 2D/ bulk 3D, and quasi-2D, depending on the amount of intercalated (PEA)<sub>2</sub>PbI<sub>4</sub>. The perovskite LED device structure was ITO/ZnO NPs/perovskite/poly-TPD/MoO<sub>3</sub>/Ag (NPs, nanoparticles), and the perovskite here had the compositional format of  $[(PEA)_2PbI_4]_x[FA_{0.98}Cs_{0.02}PbI_3]_{1-x}$ . The highest radiance  $R_{max}$  was ~191.5 W sr<sup>-1</sup> m<sup>-2</sup> (V = 2.5 V, EQE = 7.70%). The extrapolated  $T_{50}$  was 200 h at constant voltage with an initial  $R \sim 10$  W sr<sup>-1</sup> m<sup>-2</sup> (Figure 1b).

Single Halide Quantum Dot in Mixed Halide Perovskite Matrix Perovskite LED (Red,  $T_{50} = 2400$  h, 2021). Liu et al. reported red perovskite LEDs with a lifetime beyond the level of 1000 h by embedding single halide perovskite (CsPbI<sub>3</sub>) quantum dots in a mixed halide (PEA<sub>2</sub>Cs<sub>n-1</sub>Pb<sub>n</sub>(I<sub>0.6</sub>Br<sub>0.4</sub>)<sub>3n+1</sub>) perovskite matrix (Figure 2a).<sup>52</sup> The device structure consisted of ITO/poly-TPD/LiF/perovskite/TPBi/LiF/Al. The quantum dot-in-matrix perovskite LED achieved a maximum EQE of around 18% and maintained an EQE of approximately 13% under a high injection condition (J = 100 mA cm<sup>-2</sup>), whereas the quantum dot-only perovskite LEDs suffered from severe EQE droop.  $T_{50}$ , with  $L_0 = 100$  cd m<sup>-2</sup>, was estimated to be 2100 h (as



Figure 3. Core/shell nanocrystalline perovskite LEDs with a half lifetime longer than 30 000 h (@L=100 cd m<sup>-2</sup>). (a) Schematic illustration of the in situ core/shell structure. (b) TEM image of the core/shell perovskite nanograin surrounded by BPA. (c) High-resolution HAADF-STEM image of the box region in (b). (d) Luminance vs operational time of the core/shell perovskite LED with different original luminance values. (e) The half lifetime from the accelerated lifetime test of the core/shell PeLEDs. The open circle is the extrapolated half lifetime (~30 000 h) for initial luminance of 100 cd m<sup>-2</sup>. Images reprinted with permission from ref 49. Copyright Springer Nature 2022.



Figure 4. Green perovskite LED with MOF+ perovskite ( $T_{50} = 50$  h). (a) Schematic of the LED structure. (b) LED stability tests for the Cs-PeMOF device under low injection current and a high injection current (inset). Images reprinted with permission from ref 53. Copyright 2021, Springer Nature.

shown in Figure 2b). When the hole injection layer was replaced with PEDOT:PSS:PFI (PFI referring to perfluorinated ionomer), the estimated  $T_{50}$  ( $L_0 = 100$  cd m<sup>-2</sup>) further improved to 2400 h, as the deposition of perovskite using a polar solvent was more compatible with the polar hole injection layer, thereby resulting in fewer interfacial vacancy sites (as shown in Figure 2c). The matrix can reduce the carrier density and therefore reduce Auger recombination. Meanwhile, the matrix works as a protection layer to the quantum dots, which can also epitaxially passivate the surface defects. Moreover, the GIWAXS results have shown that the crystallinity of the QDs is improved when embedded in the matrix. Furthermore, the Mn doping leads to compressive lattice strain in QDs and allows for lattice matching between QDs and the perovskite matrix, which can significantly inhibit the halide mixing. The estimated lifetime was calculated using the following equation:

$$L_0^{"} \times T_{50} = \text{const.} \tag{1}$$

where  $L_0$  is the initial luminance, *n* is the acceleration factor, and const. means constant. Lifetimes at different luminance values can be measured to decide the acceleration factor; then,

# Small sized (~4 nm) CsPbBr<sub>3</sub> quantum dots perovskite LED with ultra-low trap density



Figure 5. Small-sized (~4 nm) CsPbBr<sub>3</sub> quantum dots blue perovskite LED with ultralow trap density, and  $T_{50}$  was 12 h. (a) Schematic illustration of the ligand exchange process driven by acid etching. (b) Photoluminescence of the quantum dot film and electroluminescence of the perovskite LEDs. (c) The operational half-lifetime  $T_{50}$  of the perovskite LEDs at an initial luminance of 102 cd m<sup>-2</sup>. Images reprinted with permission from ref 56. Copyright 2021, Wiley-VCH.

the lifetime at a recommended standard testing condition ( $L_0$  = 100 cd m<sup>-2</sup>) can be decided according to eq 1.

Core/Shell Nanocrystal Perovskite LEDs with Estimated Half Lifetime Longer than 30 000 h (Green,  $T_{50}$  > 30 000 h, 2022). In a recent work by Lee and co-workers, high-efficiency (peak EQE = 28.9%) and high-brightness (maximum luminance ~ 470 000 cd m<sup>-2</sup>) perovskite LEDs were achieved with simultaneous ultralong half lifetime (520 h at 1000 cd m<sup>-2</sup> and estimated >30 000 h at 100 cd m<sup>-2</sup>).<sup>49</sup> The achievement of a half lifetime exceeding 30 000 h for the core/ shell perovskite nanocrystals brings great promise for the commercialization of perovskite LEDs in displays and lighting applications. The formula of the 3D perovskite film is (FA<sub>0.7</sub>MA<sub>0.1</sub>GA<sub>0.2</sub>)<sub>0.87</sub>Cs<sub>0.13</sub>PbBr<sub>3</sub>. The key strategy involved using benzylphosphonic acid (BPA) as an additive to form core/shell perovskite nanocrystals with a size of 10 nm. BPA was used for post-treatment to form in situ nanostructures of the perovskite crystal to avoid the ionic defects with low formation energy which usually cause ion migration and carrier trappings. The BPA-surrounded nanocrystals exhibited strong carrier confinement, which facilitated fast charge transport and high internal quantum efficiency (IQE), resulting in an ultralow driving voltage of 2.7 V at a luminance of 10 000 cd  $m^{-2}$ . Figure 3 provides more details on this strategy, including a schematic of the core/shell structure in Figure 3a, TEM and STEM images of the nanocrystals surrounded by BPA in

Figure 3b,c, and half-lifetime measurements with different initial luminance values in Figure 3d,e. The estimated lifetime for an initial luminance of 100 cd  $m^{-2}$  is above 30 000 h.

Perovskite-in-MOF Green Perovskite LED (Green, T<sub>50</sub> = 50 h, 2021). The issue of ion migration in perovskite materials represents a significant and inherent challenge for achieving high-performance perovskite LEDs. Extensive efforts have been devoted to addressing this issue.<sup>54,55</sup> Tsai et al. proposed the method of mixing perovskite with MOF to protect the perovskite against ion migration, crystal merging, and interfacial corrosion (Figure 4a).<sup>53</sup> Consequently, the luminance was as high as  $1.2 \times 10^5$  cd m<sup>-2</sup> (@346.1 mA cm<sup>-2</sup>) while the highest EQE was 15.96% ( $@58.8 \text{ mA cm}^{-2}$ ), owing to the localized carrier recombination. The device structure was ITO/PEDOT:PSS/PFI/PeMOF/TPBi/LiF/Al (PeMOF, perovskite-MOF). As for the Cs-PeMOF (perovskite material is CsPbBr<sub>3</sub>),  $T_{50}$  tested at mild injection conditions (J = 25 mAcm<sup>-2</sup>, peak  $L \sim 700$  cd m<sup>-2</sup>) was 50 h (Figure 4b), but  $T_{50}$  was less than  $\sim 1$  h when the PeMOF LED was tested at high injection conditions ( $J = 100 \text{ mA cm}^{-2}$ , peak  $L \sim 10^4 \text{ cd m}^{-2}$ ). The electroluminescence degradation was ascribed to the interface polarization. Interface polarization usually comes from the difference of electronic properties between perovskite layer and electron/hole injection layers, and it can cause redistribution of charge carriers at the interfaces, with potential negative effects such as trap states formation or charge



Figure 6. Dipolar molecular stabilizer to suppress the ion migration and prevent the formation of lead iodide. (a) Schematic of the LED structure. (b) Molecular structure of the SFB10. (c) SEM image of the control perovskite film. (d) SEM image of the SFB10-stabilized perovskite film. (e) Operational lifetimes comparison of the device with and without SFB10. (f) Half lifetime ( $T_{50}$ ) with different initial radiances. Images reproduced with permission from ref 48. Copyright Springer Nature 2022.

accumulations. Therefore, it is important to minimize the negative effects of interface effects from the interface polarization to get high performance perovskite LEDs.

Small-Sized (~4 nm) CsPbBr<sub>3</sub> Quantum Dots Perovskite LED with Ultralow Trap Density (Blue,  $T_{50} = 12$  h, **2021).** In their study, Bi et al. demonstrated the development of a stable, single-halide pure blue perovskite LED with an emission peak of 460-470 nm, in accordance with the National Television System Committee (NTSC) standard. The LED was fabricated using small-sized (~4 nm) CsPbBr<sub>3</sub> quantum dots, which contributed to its stability and monochromatic emission properties.<sup>56</sup> Figure 5a shows the ligand exchange process driven by acid etching for the CsPbBr<sub>3</sub> quantum dots used in the study. Capping ligands (oleylamine (OAm) and oleic acid (OA)) are exchanged to didodecylamine (DDDAM) and PEA ligands. During this process, the imperfect octahedrons with halide vacancies are removed and the uncoordinated Pb<sup>2+</sup> ions are passivated. Less halide vacancies and surface defects contribute to enhanced PLQY and stability. Figure 5b displays the photoluminescence and electroluminescence spectra of the quantum dot film and the perovskite LEDs, respectively. The authors were able to achieve a  $T_{50}$  of 12 h with an initial luminance of 102 cd m<sup>-2</sup>, as shown in Figure 5c. This is a significant improvement compared to the short lifetimes typically observed in most pure blue perovskite LEDs, which often last only seconds or minutes. To address the surface defect problems associated with most small-sized quantum dots, the authors performed acid etching and ligand exchange to reduce the trap density. The device structure used in the study was ITO/PEDOT:PSS/ PVK/CsPbBr<sub>3</sub> quantum dots/ZnO/Ag. The perovskite LED demonstrated the highest luminance of 3850 cd m<sup>-2</sup> at a current density of 330 mA cm<sup>-2</sup>. The peak EQE was 4.7% at a current density of 17.8 mA cm<sup>-2</sup> and a luminance of 561 cd m<sup>-2</sup>. The authors also tested the  $T_{50}$  of nonencapsulated devices under ambient conditions. At an initial luminance of 102 cd m<sup>-2</sup> (driving at a current density of 12.5 mA cm<sup>-2</sup>), the device showed a lifetime  $T_{50}$  of 12 h. However, when the initial luminance was increased to 552 cd m<sup>-2</sup>,  $T_{50}$  was reduced to 100 min.

#### LIGAND ENGINEERING

Akin to the previous approach, ligand engineering is another effective strategy for enhancing the lifetime of perovskite LEDs. Ligand engineering in PeLEDs is a fascinating strategy, focusing on the modification of the ligands in perovskite materials to improve the performance and stability of the LEDs. Ligand engineering addresses these issues by modifying





Figure 7. Color-stable mixed halide nanocrystal-perovskite LED. (a) Schematic of the MAPb $(I_{1-x}Br_x)_3$  nanocrystal-LED architecture and a SEM image showing the cross-section of a device. (b) Energy band diagram of the materials used in these LEDs. (c) Operational stability of ethylenediaminetetraacetic acid (EDTA) and glutathione treated (E+G-treated) NC-LEDs measured in air at a constant current of 0.1 mA cm<sup>-2</sup> (initial luminance  $L_0 = 22$  cd m<sup>-2</sup>), 1 mA cm<sup>-2</sup> ( $L_0 = 141$  cd m<sup>-2</sup>), and 10 mA cm<sup>-2</sup> ( $L_0 = 585$  cd m<sup>-2</sup>). (d) Electroluminescence spectra of nanocrystals-LEDs with E+G ligand-treated nanocrystal layers with constant current densities of 1 mA cm<sup>-2</sup>. Images reprinted with permission from ref 3. Copyright Springer Nature 2021.

the organic and inorganic molecules, known as ligands, which are bound to the nanocrystal surfaces of perovskite. The ligands can significantly affect the material's properties, including its electronic structure, crystallinity, and stability. The choice of surface ligands can determine whether the structure is in a Dion-Jacobson (DJ) or Ruddlesden-Popper (RP) configuration, with DJ structures typically being more stable due to a single sheet of interlayered cations that prevent unstable van der Waals gaps. DJ and RP perovskites are two different classes of layered perovskite materials. They are named after the researchers who first reported their structures. DJ perovskites are a subclass of layered perovskites that have the general formula  $A_2B_{n-1}B_n'O_6$ . In this structure, the A cations occupy the octahedral sites, while the B and B' cations occupy the square-planar sites. The layers of octahedra are separated by layers of corner-sharing octahedra. DJ perovskites are known for their special structural characteristics, including the presence of organic molecules between the layers. RP perovskites are another subclass of layered perovskites with the general formula  $A_{n+1}B_nX_{3n+1}$ . In this structure, the A cations occupy the perovskite-like layers, while the B cations occupy the rock salt-like layers. The layers are separated by the X anions. RP perovskites have a characteristic feature where the perovskite-like layers are repeated n times before transitioning to the rock salt-like layers. Additionally, ligands can inhibit ion migration, the formation of lead halides, and phase segregation in mixed-halide perovskites. The following are several representative studies that have employed the ligand engineering approach.

Perovskite LED Based on DJ Structure (Near-Infrared,  $T_{50} = 100$  h, 2019). The molecular structure has an important effect on the perovskite LED stability. For example, DJstructured perovskites have only one sheet of interlaying cations (2+) between the inorganic slabs, resulting in a high molecule dissociation energy of 7.684 eV.<sup>57,58</sup> However, RPstructured perovskites have two sheets of interdigitating cations (1+), where the existence of the small van der Waals binding energy (e.g., -9.7 meV Å<sup>-2</sup> between two PEA molecules) reduces the molecule dissociation energy to only 3.988 eV. 57,58 Consequently, the DJ-structured perovskites were reported to be more stable than the RP-structured perovskites. For instance, Shang et al. successfully achieved 100 h  $T_{50}$  with DJ-structured BAB-FAPbI<sub>3</sub> PeLEDs (BAB, 1,4bis(aminomethyl)benzene).<sup>57</sup> The device structure was ITO/ ZnO/PEIE/perovskite/TFB/MoO<sub>3</sub>/Al (PEIE, polyethylenimine ethoxylated; TFB, poly-[(9,9-dioctylfluorenyl-2,7-diyl)*alt*-4,4'-(N-(4-butylphenyl)diphenylamine)]). The perovskite formula is (BAB)  $FA_{n-1}Pb_nX_{3n+1}(X = Br, I)$ .

Dipolar Molecular Stabilizer to Suppress the Ion Migration and Prevent the Formation of Lead Iodide (Near-Infrared,  $T_{50} = 32\,675$  h, 2022). Recently, Di and coworkers reported the near-infrared perovskite LED with  $T_{50}$ longer than 10 000 h, rendering it one step closer to the OLED and quantum dot LED counterparts.<sup>48</sup> The device structure was glass/ITO/PEIE modified ZnO/perovskites/TFB/MoOx/ Au (Figure 6a), and the perovskite precursor was a mixture of FAI, PbI<sub>2</sub>, and sulfobetaine 10 (SFB-10) in DMF, where SFB-10 (Figure 6b) was introduced to interact with cations and

	peak			
device type/report year	ÊQE	peak wavelength	testing conditions	lifetime
		Near-Infrared		
Dipolar molecular stabilizer to suppress the ion migration and prevent the formation of lead iodide (7003, ref 48	22.8%	$\sim 800 \text{ nm}$	Initial $R \sim 2.1 \text{ W sr}^{-1} \text{ m}^{-2}$	$T_{50} = 32.675 \text{ h} (\sim 3.7 \text{ year, } T_{50} \text{ extranolated})$
			Initial $R \sim 3.7 \text{ W sr}^{-1} \text{ m}^{-2}$	$T_{50} = 11539$ h (~1.3 year, $T_{50}$
Interface modified perovskite LED (perovskite+dicarboxylic acids+ZnO)/	18.6%	802 nm	$f = 20 \text{ mA cm}^{-2}$ , initial $R \sim 17 \text{ W sr}^{-1} \text{ m}^{-2}$	extrapolated) $T_{50} = 682 \text{ h} (\sim 28 \text{ days})$
Surface 2D/bulk 3D heterophased perovskite LED/2019, ref 51	7.7%	810–812 nm	Initial R $\sim$ 10 W sr <sup>-1</sup> m <sup>-2</sup> , constant operational voltage	$T_{50} \sim 202.7$ h (device tested for 100 h and $T_{c0}$ extrapolated)
Perovskite LED based on DJ structure/2019, ref 57	5.2%	776 nm (when BAB to FA ratio was 25%)	$J=25$ mA cm $^{-2}$ (corresponding to the highest EQE of 5.2% and a max $R$ $\sim$ 88.5 W sr $^{-1}$ m $^{-2})$	$T_{s0} = 100 \text{ h}$
Perovksite LED with nanopatterned hole injection layer and glass substrate for heat and light management/2021, ref 69	21.2%	Red 666 nm	Initial $L \sim 100 \text{ cd m}^{-2}$	$T_{\rm 50} = 4806.7 \ {\rm h} \ (\sim 200 \ {\rm days})$
Znl3 passivated CsPbl3Br* PeLEDs/2021, ref 70	9.93%	666 nm	Initial $L \sim 100 \text{ cd m}^{-2}$	$T_{s0} = 2667 \text{ h} (\sim 111 \text{ days})$
Perovekite quantum dots (single halide 1) in perovskite matrix (mixed halide $40\%$ Br)/ 2021, ref S2	18%	650 nm	Initial $L \sim 100 \text{ cd } \text{m}^{-2}$	$T_{50} = 2400 \text{ h} (\sim 100 \text{ days}) (\text{estimated} \text{by eq 1})$
$CsPbI_3$ nanowires PeLED with ZnO as electron injection layer/2020, ref 71	6.2%	620 nm	Initial $L \sim 100 \text{ cd m}^{-2}$	$T_{50} = 694 \text{ h} \text{ (estimated)}$
Lead and halide defects passivated perovskite LED/2020, ref 72	20.9%	694 nm	$J = 2.5 \text{ mA cm}^{-2}$ ; initial $L \sim 25 \text{ cd m}^{-2}$	$T_{50} = 14 \text{ h}$
Ligand engineered color-stable MAPb( $\mathbf{I}_x\mathbf{Br}_{1-x})_3$ nanocrystals red perovskite	20.3%	630 nm (for E+G)	$f = 0.1 \text{ mA cm}^{-2}$	$T_{50} = 340 \min(\sim 5.7 h)$
LED/2021, ref 3			$J = 1 \text{ mA cm}^{-2}$	$T_{50} = 130 \min (\sim 2.2 \text{ h})$
			$J = 10 \text{ mA cm}^{-2}$	$T_{50} = 16 \text{ min}$
		Green		
Core/shell nanocrystal perovskite LEDs/2022, ref 49	28.9%	540 nm	Initial $L = 100 \text{ cd } \text{m}^{-2}$	$T_{50}$ > 30 000 h (extrapolated)
			Initial $L = 1000 \text{ cd m}^{-2}$	$T_{50} = 520 \text{ h}$
All inorganic device with the addition of alkali-metal ions/2020, ref 73	11.05%	519 nm	Initial $L \sim 120 \text{ cd m}^{-2}$	$T_{50} = 255 \text{ h}$
Cs/TFA-based small grained perovskite LED, surface defects passivation/ 2019, ref $74$	10.5%	518 nm	Initial $L \sim 100 \text{ cd m}^{-2}$	$T_{50} = 250 \text{ h}$
MABr passivated CsPbBr <sub>3</sub> perovskite LED/2019, ref 4	20.3%	525 nm	Initial $L \sim 100 \text{ cd m}^{-2}$	$T_{ m 50} \sim$ 100 h (estimated by eq. 1)
			Initial $L \sim 7130 \text{ cd m}^{-2}$	$T_{50} \sim 10  \mathrm{min}$
Perovskite+MOF/2021, ref 53	15%	518 nm (for Cs-PeMOF) Blue	$J=25~{\rm mA~cm^{-2}},$ peak $L\sim700~{\rm cd~m^{-2}}$	$T_{50} = 50 \text{ h}$
Sandwich panel (SWP) of CsPbBr <sub>3</sub> quantum dots/ZnCl <sub>2</sub> /CsPbBr <sub>3</sub> quantum dots, $L_{\rm max}=10~410$ cd m <sup>-2</sup> /2022, ref 75	5%	469 nm	Initial $L \sim 100 \text{ cd m}^{-2}$	$T_{50} = 59 \text{ h}$
Small sized ( ${\sim}4~{\rm nm})$ CsPbBr3 quantum dots perovskite LED with ultralow trap density/2021, ref 56	4.7%	470 nm	J = 12.5 mA cm <sup>-2</sup> ; unencapsulated device in ambient condition	$T_{50} = 12 \text{ h}$
Multication perovskite combined with "insulator/perovskite/insulator" structure/2020, ref 19	2.01%	484 nm	$J = 25 \text{ mA cm}^{-2}$	$T_{50} = 300 \text{ min } (5 \text{ h})$
Perovskite LED with incorporation of ABA ligand to diminish the van der Waals gap/2020, ref $59$	10.11%	484 nm	$J = 0.3 \text{ mA cm}^{-2}$	$T_{50} = 81.3 \text{ min } (\sim 1.4 \text{ h})$
Perovskite LED based on quantum confined Br perovskite nanostructure/ 2019, ref $76$	9.5%	483 nm	Initial $L \sim 100 \text{ cd m}^{-2}$	$T_{50} \sim 250 \text{ s} (\sim 0.07 \text{ h})$
<sup>a</sup> NIR, near-infrared; RP, Ruddlesden-Popper; DJ, Dion–Jacobson; I	'EO, poly(	ethylene oxide); ODEA, 2,	2'-[oxybis(ethylenoxy)]diethylamine; BAB, 1,4-bis(amir	nomethyl)benzene; E+G, mixture of

anions at the perovskite (FAPbI<sub>3</sub>) grain boundary to suppress the ion migration under electric field and prevent the formation of PbI<sub>2</sub>. Figure 6c,d shows the SEM images of perovskite film with and without SFB10 as a stabilizer. Figure 6e is the lifetime comparison of devices with and without SFB10. Figure 6f is the half lifetimes with different initial radiances. Consequently, in addition to the ultralong lifetime, a high EQE of 22.8% was also achieved at J = 17 mA cm<sup>-2</sup>. The functional groups on the SFB-10 stabilizer can bind with A site cations (FA<sup>+</sup>), B site cations (Pb<sup>2+</sup>), and anions (I<sup>-</sup>) at the perovskite boundaries, which is a kind of zwitterionic ligand passivation of perovskite nanocrystals.

Color-Stable Mixed Halide Nanocrystal-Perovskite **LED** (Red,  $T_{50} = 340 \text{ min}$ , 2021). The conundrum of phase segregation, which emanates from the utilization of mixed halides, poses a significant hurdle in the realization of red perovskite LEDs with high efficiency (EQE > 20%). To tackle this quandary, Hassan and colleagues stabilized the bandgap of mixed halide MA nanocrystal perovskites (MAPb- $(I_x Br_{1-x})_3$  nanocrystals) via the manipulation of ligands.<sup>3</sup> The authors employed ligand engineering to decrease active defects in their perovskite nanocrystals and found that the use of an equimolar mixture of ethylenediaminetetraacetic acid (EDTA) and glutathione was particularly effective in suppressing nonradiative recombination. The mixed halide perovskite nanocrystals were treated with multidentate ligands to suppress the halide segregation. The key is to clean the nanocrystal surface through removal of Pb atoms. Nanocrystals were treated with ligands EDTA and reduced L-glutathione, and they bind strongly to Pb<sup>2+</sup> on the surface. The ligand treatment also contributes to the halide composition changes and the confinement effects that lead to emission wavelength changes. EDTA leads to a small broadening in the emission spectra. Glutathione gives the most stable spectra but sacrifices efficiency. Glutathione is more strongly bound to the crystal surface compared to EDTA. The binding energies of glutathione and EDTA to the perovskite surface are -1.85and -1.60 eV. Furthermore, the intermolecular hydrogen bonding that occurs between the carboxylic moieties of glutathione and EDTA confers supplementary stability to surface-adsorbed molecules, resulting in a binding energy of -4.45 eV, and the use of EDTA and glutathione increases the formation energy of iodine Frenkel defects to 0.18 eV, compared to 0.03 eV from the untreated PbI2-termited perovskite surface; therefore, the halide segregation is more inhibited. The device structure used in their study was ITO/ PEDOT:PSS/Poly-TPD/TFB/perovskite nanocrystals/TPBi/ LiF/Al (as shown in Figure 7a,b). The best EQE achieved was 20.28% at a bias voltage of 3.4 V, with a current density of approximately 0.1 mA cm<sup>-2</sup> and a peak wavelength centered at 620 nm. The  $T_{50}$ s at current densities of 0.1, 1, and 10 mA  $cm^{-2}$  were 340, 130, and 16 min, respectively (as shown in Figure 7c). Furthermore, Figure 7d illustrates the stability of the electroluminescence spectrum under constant current driving of 1 mA  $cm^{-2}$ .

Blue Perovskite LED with the Incorporation of 4-(2-Aminoethyl)benzoic Acid (ABA) Ligand to Diminish the van der Waals Gap (Blue,  $T_{50} = 81.3$  min, 2020). Ren et al. reported efficient blue perovskite LEDs by incorporating ABA ligands to enhance the energy transfer and passivate the defects.<sup>59</sup> Perovskite (PEA<sub>x</sub>PA<sub>2-x</sub>(CsPbBr<sub>3</sub>)<sub>n-1</sub>PbBr<sub>4</sub>) was passivated by the incorporation of the ABA ligands to reduce the van der Waals gap between perovskite layers. The device structure was ITO/PVK/perovskite/TPBi/LiF/Al. The maximum luminance was 513 cd m<sup>-2</sup> at 5.1 V, and the best EQE was 10.11% (electroluminescence centered at 484 nm). When tested with a constant current density of 0.3 mA cm<sup>-2</sup>, the device  $T_{50}$  (dropping to half of the initial efficiency in this work) was 81.3 min.

It is worth mentioning that the Cu perovskite-based (or Cu treated/doped) blue perovskite LED can show a longer lifetime due to better thermal tolerance (because of increased lattice binding energy and improved short-range order of the lattice) and a higher lattice formation energy.<sup>60</sup> For instance, Wang et al. reported the Cs<sub>3</sub>Cu<sub>2</sub>I<sub>5</sub> nanocrystal-based deep-blue (~445 nm) perovskite LEDs with a  $T_{50}$  of ~108 h and EQE of 1.12%.<sup>61</sup> The device structure was Al/LiF/TPBi/Cs<sub>3</sub>Cu<sub>2</sub>I<sub>5</sub>/NiO/ITO.

It should be noted that, while the prior discussion primarily centers on enhancing stability in the perovskite layer, the nanoscale strategies discussed are also applicable to the adjacent injection layers. For instance, Sun et al. have demonstrated bright and stable near-infrared PeLEDs through the introduction of a multifunctional molecule, 2-(4-(methylsulfonyl)phenyl) ethylamine (MSPE). This molecule serves a dual purpose: it not only reduces nonradiative decay within the perovskite layer but also mitigates luminescence quenching at the perovskite/injection layer interfaces.<sup>62</sup> This resonates with advancements in quantum dot LED stability enhancement, where employing ZnO as a charge injection layer has significantly extended the operational lifespan of quantum dot LEDs. It underscores the crucial role that charge injection layers and their interfaces with the emission layer play in determining the overall lifetime of LEDs.

The typical reports for near-infrared, red (R), green (G), and blue (B) PeLEDs in recent years are summarized in Table 1.

#### **DISCUSSION AND OUTLOOK**

The common procedures for testing and comparing the operational lifetime of perovskite LEDs are summarized below. It should be noted that these procedures are not exhaustive and may not apply to every individual case. Typically, lifetime measurements (mainly  $T_{50}$ ) are performed either with packaged devices in air or with nonpackaged devices in a N<sub>2</sub>-filled glovebox. However, perovskite LED device packaging can be a separate topic, which is beyond the scope of this Perspective.<sup>63</sup> In addition, the initial luminance used to test  $T_{50}$ is typically around 100 cd m<sup>-2</sup>, which falls within the low- to moderate-injection regions. However, most perovskite LEDs operating at high injection currents continue to experience rapid degradation due to intrinsic and severe ion migration and Joule heating issues caused by various defects (inside perovskite crystals, at perovskite crystal surfaces, at interfaces, etc.).

Upon researching the literature, we have observed some minor discrepancies in the method of counting the lifetime of perovskite LEDs, i.e., whether it should be measured from the device turn-on point or the luminance peak value point. As a result, the  $T_{50}$  standards are not consistent across various reports, as it is unclear whether it should be half of the initial luminance ( $L_0$ ) or the peak luminance ( $L_{max}$ ). Furthermore, the warm-up phenomenon is quite common in perovskite LED devices, and this can cause some discrepancies in the  $T_{50}$  testing results using either of the two methods mentioned above.

#### Table 2. Record Lifetimes for $OLED^a$

device structure//report year	peak EQE	peak wavelength	testing conditions	lifetime			
	Red						
TADF-based hybrid tandem four-color white OLED/Year 2020, ref 77	42.9%	580 nm	$L_0 = 1000 \text{ cd } \text{m}^{-2}$	$T_{50} = 5570$ h			
Dual acceptor TADF emitters for orange-red OLED, dopant: DTXO-TPA2/ Year 2022, ref $78$	24.98%	588 nm	$L_0 = 1000 \text{ cd m}^{-2}$	$T_{50} = 1392$ h			
Green							
4CzIPN TADF green OLED with emission zone control/Year 2022, ref 79	20%	530 nm	$L_0 = 1000 \text{ cd } \text{m}^{-2}$	$T_{95} = 4500 \text{ h}$			
Green TADF OLED with hole transporter 4DBFHPB/Year 2020, ref 80	19.2%	~540 nm	$L_0 = 1000 \text{ cd } \text{m}^{-2};$ $V \sim 4.07 \text{ V}$	<i>T</i> <sub>50</sub> ~24 000 h			
	Blue						
ITO/NPD/T2fQ/DBFPO:TDBADI/TSPO1/LiF/Al //Year 2021, ref 81	41.2%	458 nm	$L_0 = 1000 \text{ cd m}^{-2};$ V ~ 3.2 V	$T_{50} = 14$ h			
Top emission hyperfluorescent OLED with PtON7-dtb as phosphorescent sensitizer/Year 2021, ref 82	48.9%	473 nm	$L_0 = 1000 \text{ cd } \text{m}^{-2}$	$T_{50} = 253.8$ h			
Sky-blue TADF OLED with hole transporter 4DBFHPB/Year 2020, ref 80	21.5%	~490 nm	$L_0 = 500 \text{ cd } \text{m}^{-2}$	$T_{50}\sim 1700~{\rm h}$			
	White						
Hybrid tandem white OLED based on TADF blue emitter stabilized with phosphorescent red emitter/Year 2020, ref 77	126.2%	white light: 495, 556, and 606 nm	$L_0 = 1000 \text{ cd m}^{-2}$	$T_{50} = 12\ 600\ h$ (extrapolated)			
<sup><i>a</i></sup> TADF, thermally activated delayed fluorescence.							

To the best of our knowledge, the lifetime for single halide perovskite LEDs has surpassed 30 000, 2000, 30 000, and 50 h for near-infrared, red, green, and blue, respectively, when tested with  $L_0 \sim 100$  cd m<sup>-2</sup>. Nevertheless, in our opinion, the color/spectral stability after a long working time is still a challenge for mixed halide perovskite LEDs, and the phase segregation not only is an impediment to color stability but also results in device failure. Similar problems also exist for mixed halide blue perovskite LEDs. In terms of lifetime comparisons, it is common for red, green, and blue OLEDs to achieve  $T_{50}$  lifetimes of 1 million, 100 000, and 10 000 h, respectively, at an initial brightness of 100 cd  $m^{-2.64}$  (Table 2 summarizes the lifetimes of OLEDs from a few selected reports.) Additionally, both OLED and quantum dot LED technologies have achieved  $T_{95}$  lifetimes exceeding 5000 h, which meets the industry requirements. Notably, white light OLEDs already achieved a lifetime of 100 000 h at 1000 cd m<sup>-2</sup> back in 2012.<sup>65</sup> Furthermore, both fluorescent and phosphorescent OLEDs achieved  $T_{50}$  lifetimes of 10 000 to 100 000 h for RGB colors at 1000 cd m<sup>-2</sup> approximately 15 years ago.<sup>66</sup> For quantum dot LEDs,  $T_{50}$ 's with the initial luminance of 1000 cd  $m^{-2}$  have been more than 3000, 1000, and 20 h for red, green, and blue, respectively, according to the discussion by Chen et al. in 2019.<sup>67</sup> Based on the provided data, there remains a significant disparity in the lifespan between perovskite LEDs and OLEDs/quantum dot LEDs, primarily due to the unresolved issue of halide ion migration.

In addition, although the utilization of alternating current mode driving has demonstrated some promise in remedying halide segregations, further methodical investigations are warranted to ascertain how this approach can be effectively employed to attain prolonged  $T_{50}$  values exceeding 1000 h. It appears that a combination of single-halide perovskites with quantum engineering to blue-shift the emission wavelength could be a promising and reliable strategy for improving the operational stability of red/blue perovskite LEDs soon. However, the halide ion segregation problem is inherent to mixed-halide perovskites, and further exploration is needed before we can draw definitive conclusions on how to achieve high-performance red/blue mixed-halide perovskite LEDs using generic strategies.

Achieving ultralong-term stable perovskite LEDs requires the use of "nano" strategies, including dimension control and ligand engineering, which have been shown to be extremely effective.  $T_{50}$  values longer than 30 000 h have been achieved for both near-infrared and green perovskite LEDs using these approaches.<sup>48,49</sup>

To date, a definitive solution to completely address the issue of ion migration in perovskite LEDs has not been identified. However, there have been numerous reports regarding efforts to alleviate halide ion migration, also known as halide segregation. Ion migration poses a significant challenge, particularly for LEDs, as their operating voltage is considerably higher than that of solar cells. The elevated voltage levels in LEDs can exacerbate the migration of ions within the perovskite material.

Researchers have explored various approaches to mitigate halide ion migration and improve the stability of perovskite LEDs. These efforts include modifying the composition of the perovskite material, engineering interfaces within the device, and implementing protective layers to inhibit ion migration, and these methods share the common point of material engineering at a "nano" scale level. These approaches recognize the importance of manipulating the composition and structure of perovskite materials at extremely small dimensions to control and mitigate ion migration.

By tailoring the nanostructure of the perovskite layer, researchers can influence the movement of ions and their aggregation within the material. This can be achieved via precise control of parameters such as grain size, crystallinity, and surface morphology. Additionally, nanoengineering techniques enable the creation of interfaces and heterostructures within the device that can help impede ion migration. These interfaces can act as barriers, hindering the movement of ions and reducing their detrimental effects on device performance. Furthermore, the implementation of nanoscale protective layers can provide an additional level of defense against ion migration. These layers can serve as diffusion barriers or ion-blocking structures, preventing the migration of ions from the perovskite layer to other regions of the device.

By focusing on material engineering at the nano scale, researchers aim to gain finer control over the behavior of ions

within perovskite LEDs, ultimately improving their stability and performance. Further advancements in this field contribute to the enhanced reliability and efficiency of perovskite-based optoelectronic devices.

To summarize, improving the operational stability of perovskite LED devices necessitates a gradual and systematic approach. First, the fabrication process must be devoid of water and oxygen, followed by effective encapsulation. Second, the selection of materials for each layer should be meticulous, with inorganic materials typically exhibiting greater stability than organic ones. By avoiding van der Waals gaps between perovskite sheets, DJ perovskites can be more stable than RP perovskites. It is also important to note that mixed-halide perovskite LEDs are susceptible to phase segregation, and therefore, the use of quantum-confined single-halide perovskite materials is recommended to attain stable red/blue perovskite LEDs. Third, interfacial treatments and perovskite passivation play a crucial role in reducing defects and trap states, which can positively impact the reduction of Joule heating, crystal merging, and electrode degradation. Finally, ion migration is a significant issue that requires a deeper understanding of the fundamental physics underlying it. Addressing this issue necessitates significant scientific attention if the lifetime of perovskite LEDs is to be enhanced to meet commercial standards.

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# Notes

The authors declare no competing financial interest.

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