Developments in the Study of Perovskite Light-Emitting Diode Instability

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Abstract: Perovskite light-emitting diodes (PeLEDs) exhibited significant potential for application in advanced display technologies and solid state lighting (SSL), owing to their superior photoelectric performance. However, compared with conventional LED technologies, the instability and disparities across various aspects of PeLEDs have emerged as the primary bottleneck hindering their industrialization. This paper systematically reviews the study of PeLEDs' instability and elucidates that the self-reinforcing feedback cycle between ion migration and phase separation constitutes a critical mechanism underlying device performance degradation. To enhance stability, this work discusses material innovation-based strategies such as ion doping, ligand engineering, and dimensional regulation for component optimization. Additionally, structural improvement approaches, including voltage reduction, insertion layers, and thermal management, are analyzed from the perspective of device engineering. By underscoring the significance and urgency of PeLED instability research, this paper aims to provide concrete insights and methodologies to overcome the stability bottleneck of PeLED devices and expedite the practical implementation of high-stability PeLEDs.

1 INTRODUCTION

In recent years, perovskite materials have emerged as promising candidates for advanced display technologies and next-generation lighting systems, owing to the outstanding photovoltaic attributes, including ultra-high light absorbance, balanced charge carrier transport capabilities, adjustable energy band structures and simple preparation process (Fakharuddin et al., 2022; Han et al., 2022). In terms of photovoltaic efficiency, perovskite light-emitting diodes (PeLEDs) have achieved parity with conventional LEDs, and in some aspects, even surpassed them. Currently, the external quantum efficiency (EQE) of the most advanced monochromatic PeLEDs reached 28.7% (at 638 nm), 30.8% (at ~530 nm), and 26.4% (at 480 nm), respectively (Kong et al., 2024; Bai et al., 2024); However, in terms of stability, PeLEDs still have a significant gap compared to traditional LEDs. Commercially available LEDs need to meet a minimum lifespan requirement of at least 10,000 hours to balance their environmental impact (Zhang et al., 2025). Currently, the recorded lifetimes of red, green, and blue PeLEDs are 48,000 hours (T95 at 1,000 cd/m2), 12,500 hours (T50 at 100 cd/m2), and 12 hours (T50 at 102 cd/m2), respectively (Yan et al., 2023; Chen et al., 2023; The insufficiency and disparity in stability, especially the obvious lag in the development of blue PeLEDs, have become the key bottleneck restricting the commercialization process of PeLEDs (Bi et al., 2021).

This paper reviews the research on the instability of PeLEDs, summarizes the instability mechanism of the self-reinforcing feedback cycle of ion migration and phase separation, and lists various solutions in the dimensions of material innovation and device engineering to overcome stability limitations, hoping to accelerate the practical application process.

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2 INSTABILITY MECHANISM OF PELEDS

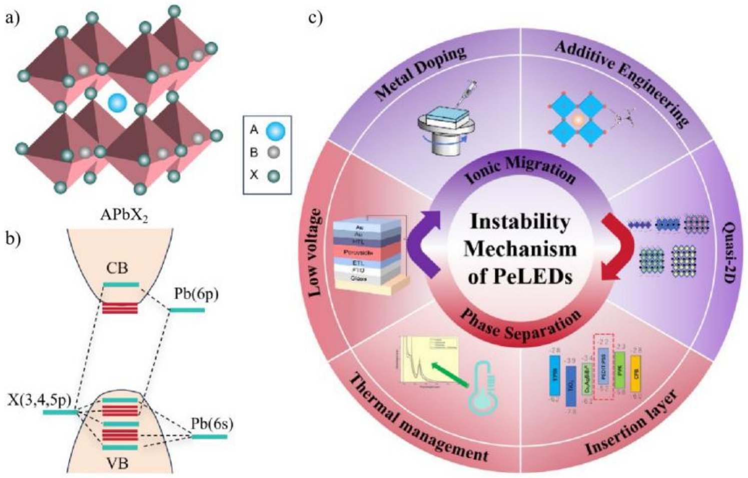

Figure 1: a) Perovskite crystal structure; b) Perovskite energy band structure; c) Instability mechanism and its optimization strategy.

2.1 Perovskite Luminescent Materials

Perovskite materials are defined as metal halides with an ABX3 crystal structure (Figure 1a). The ideal perovskite crystal consists of corner-sharing [BX6] 4-octahedra, forming an isometric system. Here, A mainly denotes alkali metal cations or smaller organics (Cs+, CH3NH3+, etc.), B symbolizes mainly divalent metal cations (lead ion, tin ion), and X represents a halide ion. Taking the band structure of lead halide perovskites (Figure 1b) as an example, the valence band (VB) structure primarily arises from antibonding hybrid orbitals formed by the interaction between X anion np orbitals and Pb cation 6s orbitals, with the np orbitals of halide/pseudohalide (X) components providing the dominant contribution to the orbital composition. The conduction band (CB) structure originates from the hybridized interaction between the 6p orbitals of Pb cations and the np orbitals of X anions, with the 6p orbitals of Pb ions being dominant. Although cations do not directly contribute to the formation of frontier orbitals, their differences in ionic radius can indirectly affect the band gap width and band dispersion relationship through lattice distortion effects (Akkerman et al., 2018).

The unique molecular composition and band structure of perovskites endow them with an outstanding defect tolerance mechanism. Unlike deep-level defects in traditional semiconductors that significantly deteriorate carrier transport properties, intrinsic defects in perovskites (such as vacancies and interstitial atoms) are mostly shallow-level states with minor impacts due to the contributions of Pb atom's s and p orbitals (Akkerman et al., 2018). Further, their low formation energy characteristics cause defects to preferentially distribute in the band edge regions near the VB top and CB bottom rather than within the semiconductor's forbidden energy region, thus having little effect on carrier relaxation and recombination processes (Kovalenko et al., 2017). This unique defect distribution pattern effectively suppresses non-radiative recombination channels, endowing the material with extremely high fluorescence quantum yields (introducing TOP-PbI2 can increase the PLQY to nearly 100%), an ultra-broad color range (close to 1.4 times the NTSC specification), and ultra-pure color emission characteristics (Liu et al., 2018). Combined with the quantum confinement effect, perovskite materials exhibit performance boundaries that surpass traditional luminescent materials, making them strong contenders for next-generation optoelectronic materials and widely used in lasers, light-emitting diodes, and next-generation displays and other luminescent fields.

2.2 Ion Migration

The unique three-dimensional corner-sharing [BX6]4 octahedra structure of perovskite materials, which endows them with excellent defect tolerance, also constitutes a conduction path for ion migration (mainly the migration of A and X cations). Compared with perovskite devices, PeLEDs have more severe ion migration phenomena. On the one hand, the fabrication of PeLEDs usually requires the introduction of excessive organic halide salts, where the free halide ions (X-) and organic cations (MA+/FA+) that do not participate in lattice coordination form an overly concentrated ion reservoir at the grain boundaries and surface, providing a material basis for ion migration (Jia et al., 2021). On the other hand, the perovskite active layer in PeLEDs is typically only tens of nanometers thick and needs to withstand a high voltage of >3V, resulting in a more pronounced local Joule heating effect (Lianfeng et al., 2017).

Such a high ion migration rate will lead to the aggregation of vacancy defects at perovskite interfaces, causing crystal structure distortion (Kim et al., 2020). Lattice deformation leads to the appearance of deep-level defect states and non-radiative recombination centers in the device, ultimately reducing the radiative efficiency of the perovskite emission layer. More specifically, as PeLED devices operate, the external electric field will induce charged ions to cross the interface and enter the charge transport layer (ETL), affecting the conductivity of ETL and causing current-voltage hysteresis. Even some Br- and CN- (MA+) ions will form migration paths with a diameter of 25 µm, i.e., black spots in the device (Lee et al., 2019). Yuan et al. (2016) pointed out that the external electric field will also promote electrochemical reactions in perovskite materials, accelerating the decomposition of perovskite materials and generating gaseous products such as AX2 and X or organic substances. Yuan's experiments found that as the applied electric field increased 1 V μm^{1}, the distance traveled by the gas generation path over 100 µm decreased from about 250 s to about 168 s, and the path width further expanded. Liu et al. (2021) also noted that the temperature rise during device operation will lower the migration barrier, activate ion vibrations, form defect clusters, and cause material emission thermal quenching (enhanced electron-phonon interaction, making it easier for exciton energy to be dissipated through phonon scattering).

The excessive ion migration rate caused by the preparation and luminescence of perovskite luminescent materials leads to lattice distortion and material decomposition, thereby reducing stability. This is the core principle of its instability.

2.3 Phase Separation and Environmental Impact

The microscopic kinetic origin of phase separation phenomena is constituted by ion migration, which is essentially a non-equilibrium transport process of carriers at lattice defects. When the local ion concentration exceeds the thermodynamic stability threshold, it triggers the phase separation behavior of the material system, forming a multi-phase coexistence structure with different lattice constants, bandgap energy levels, and electrical conductivity characteristics. Wang et al. (2023) pointed out that this non-uniform phase distribution would lead to the interruption of carrier transport paths, specifically manifested as a decrease in carrier mobility and a significant quenching effect of recombination luminescence. Baek et al. (2024) found that lattice distortion fields are generated at the multi-phase interfaces, inducing the initiation and propagation of microcracks. This structural defect is significantly enhanced by the synergy of the environment. For instance, after heating, the film shows enlarged grains (~50%) and cracks at the grain boundaries, which are attributed to the displacement of A-site cations, and this displacement is caused by the breaking of chemical bonds under thermal effects (Niu et al., 2017). Water and oxygen also significantly affect PeLEDs. In a high water and oxygen environment, water molecules are easily adsorbed at the perovskite grain boundaries and undergo hydrolysis reactions with organic cations (such as MA+), leading to the decomposition of the perovskite structure. Meanwhile, oxygen undergoes oxidation reactions with halogen ions, generating halogen vapor (such as I2), further exacerbating the destruction of the lattice structure and the deterioration of the device morphology (Yuan et al., 2016). Xiao et al. (2017) found that after light exposure, the Fermi level in the perovskite gap increased by 0.3 eV, and the PL peak also showed a slight shift, reflecting that phase separation can also be induced by light or applied bias, and further affecting the stability of various properties.

The above multi-scale analysis indicates that the core instability mechanism of PeLEDs is the self-reinforcing feedback cycle of ion migration and phase separation. Therefore, balancing the activity and stability of ion migration and suppressing phase separation caused by the device electric field and the external environment are the two key research directions to improve the instability of PeLEDs (Figure 1c).

3 STRATEGIES FOR IMPROVING PELEDS' INSTABILITY

Table 1: Six Common Strategies to Improve the Instability of PeLEDs

T_{50}[h]	EQE[%]	Strategy	Ref.
5 at 3 mA/cm^2	5.10%	Metal Doping	Gangishetty et al., 2019
60 at 10 mA/cm^2	15.84%	Metal Doping	Li et al., 2020
12 at 102 cd/m^2	4.70%	Additive Engineering	Bi et al., 2021
1340 at 100 cd/m^2	25.60%	Additive Engineering	Xu et al., 2025
100 at 25 mA/cm^2	5.20%	Quasi-2D	Shang et al., 2019
7691.1 at 100 cd/m^2	27.80%	Low voltage	Zheng et al., 2024
*648,500 at 1,000 cd/m^2	23.00%	Low voltage	Yan et al., 2023
1774 at 20 mA/cm^2	22.70%	Insertion layer	Yi et al., 2024
4806.7 at 100 cd/m^2	21.20%	Thermal management	Ye et al., 2021

*By extrapolation through an exponential model

3.1 Material Composition Engineering

By investigating the most advanced methods for improving the stability of PeLEDs, it lists their corresponding half-lives (T50) and external quantum efficiencies (EQE), and summarize six common stability improvement strategies (Table 1). Material composition engineering is one of the core strategies for enhancing the stability of PeLEDs, focusing on defect passivation and lattice stiffening through chemical composition optimization and crystal structure regulation, thereby effectively suppressing ion migration and slowing down the phase separation process.

In the field of ion doping, researchers have increased the migration activation energy of halide ions by introducing heteroatoms, obtaining stable perovskite crystal structures. Gangishetty et al. (2019) partially replaced Pb2+ at the B site with Mn2+ to obtain the multi-doped structure. The devices showed a 5-hour brightness half-life (T50) and excellent spectral stability, verifying the effect of ion doping. Further, Li et al. (2020) revealed the synergistic stabilization mechanism of alkali metal: Cs+ uniformly distributed in the bulk enhanced Coulomb interaction between cations and the inorganic framework, while Rb+ preferentially enriched at the grain boundaries and surface to passivate defects. This dual-ion regulation extended the device's half-life to 60 hours, highlighting the significant contribution of multi-ion cooperative engineering to structural stability.

In the field of ligand engineering, Bi et al. (2021) developed a hydrogen bromide (HBr) etching process, which was proven to remove most surface defects and excessive carboxylate ligands from the [PbBr6]4− octahedra. The pure blue PeLEDs fabricated by this process had a T50 of over 12 hours under continuous operation, setting a new record for blue device stability. Xu et al. (2025) employed a multisite cross-linking ligand approach to suppress halide ion migration in CsPbBr3 QD films, which could also effectively passivate and stabilize the perovskite surface. This strategy increased the device T50 to 1340 hours, more than six times longer than traditional structures.

In the field of dimensionality control, 3D perovskite structures were strategically modified by substituting A cations with larger counterparts to have quasi-2D geometries. Processed devices have mixed phases that can achieve strong quantum confinement. Shang et al. (2019) used a bidentate organic molecule, BAB, as a bridging molecule to fabricate PeLEDs, building upon the DJ framework, with a T50 operational lifespan of 100 hours, which is two orders of magnitude longer than that of the 3D structure. Such quasi-2D structures balance the requirements of carrier transport and structural stability through the coexistence of mixed phases, providing a new paradigm for the component design of high-performance PeLEDs.

3.2 Device Structure Design

Device structure design is another key direction for enhancing the stability of PeLEDs. It focuses on optimizing the interfaces and energy level matching between device layers to block ion migration paths and suppress the phase separation caused by the coupling effect of the electric field and the environment. It achieves a breakthrough in long-term device stability by constructing multi-dimensional barriers.

In terms of reducing voltage, Zheng et al. (2024) successfully achieved a record-low 1.7 V turn-on voltage in green PeLEDs via upgrading the emitter and charge transfer layers, significantly increasing the lifespan (T50 at 100 cd/m2) to 7,691.1 hours. This study demonstrated that lowering the turn-on voltage beneath the bandgap minimizes Joule heating, solves stability issues, extends the fluorescent lifetime. Yan et al. (2023) also achieved minimal heating effect in PeLEDs through lowering the driving voltage, achieving a high EQE of 23% at 1,000 cd/m2 and a T95 operational lifespan of over 48,000 hours.

Regarding the insertion layer, Yi et al. (2024) proposed a spatial barrier strategy for the hole transport layer (HTLs). Via lowering perovskite wettability, it effectively prevents the upper HTL from penetrating into the perovskite grain boundaries, thereby suppressing ion migration. Experimental data show that the device maintains a T50 of 256 hours at a high current density of 100 mA/cm^2 and extends the half-life to 1,774 hours at a low current density of 20 mA/cm^2. This structural innovation provides a new approach for improving the stability of high-brightness devices through the synergistic effect of physical isolation and chemical passivation.

In terms of thermal management, Ye et al. (2021) developed a collaborative device architecture that combines a Specially designed CsPbIxBr3-x perovskite bulk to minimize heating effect and enhance heat transfer of the device. This architecture achieved a working half-life of 4,806.7 hours at 100 cd/m2. Such an architecture opens up a new path for thermal stability management in high-performance PeLEDs through material-structure collaborative design.

4 CONCLUSION

This article reviews the research progress on the stability of PeLEDs, emphasizing the critical constraint that stability issues pose to their commercialization process. It delves into the core mechanism of PeLEDs' stability, highlighting the dominant role of the self-reinforcing feedback cycle between ion migration and phase separation in the degradation of device performance. To enhance stability, the article explores two major strategies: material composition engineering and device structure design. Although the lifespan of some laboratory devices has reached the minimum commercial standard for LEDs, the stability of full-color red, green, and blue displays remains uneven, with blue devices lagging significantly in efficiency and lifespan. Moreover, the lack of a unified standard for device stability testing (inconsistent initial conditions, units, and bases, and unknown testing environments) leads to poor data comparability, hindering technological iteration.

Looking ahead, the stability research of PeLEDs needs to deepen the collaborative innovation of material gene design and device integration. On one hand, by integrating high-throughput computing and machine learning technologies, the screening and optimization process of stable perovskite materials can be accelerated. On the other hand, real-time monitoring of ion migration/phase separation via in-situ techniques is essential for understanding and controlling failure mechanisms. Ultimately, through the cross-disciplinary integration of multiple fields, PeLEDs can be advanced towards high stability and long lifespan for photonic applications, unlocking their transformative potential in Environmentally friendly lighting and flexible displays.

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