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Inorganic Perovskite Composites for Light Emitting Diodes

Vahid Keshavarz [a]***, Raheleh Zarei*** [b*]***, Shima Nasibi*** [c]***, Mehdi mohabbatkhah*** [d]

[a] Department of Materials Engineering, Imam Khomeini International University, Qazvin, Iran

[b] Faculty of Chemistry, Kharazmi University, Tehran, Iran

[c] Department of Materials Science and Engineering, School of Engineering, Shiraz University, Shiraz, Iran

[d] Department of Engineering, Maku Branch, Islamic Azad University, Azerbaijan, Iran

ABSTRACT

In recent years, there has been significant interest in all-inorganic perovskite materials due to their remarkable qualities, which include extended stability, adjustable light absorption spectra, suitable energy bandgap, extensive carrier diffusion length, and elevated photoluminescence quantum yield (PLQY). These extraordinary optical characteristics and stability make them highly promising contenders for optoelectronic devices. This paper explores inorganic perovskite composites and their applications in the development of light-emitting diodes (LEDs). Firstly, the fundamental concepts of all-inorganic PeLEDs have been explicated. Subsequently, the introduction of inorganic perovskite composites PeLEDs has been presented. Particularly, we have comprehensively provide a review the synthesis methods employed for all-inorganic nanocrystals (NC) , including hot-injection, ultrasonication, room-temperature and vapor deposition techniques. Furthermore, we have outlined various strategies aimed at enhancing the efficiency of all-inorganic composite PeLEDs.

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1. Introduction

Light-emitting diodes (LEDs) have become increasingly vital in our daily lives since their introduction in the 1960s [1-4]. They have the potential to replace traditional light sources in lamps and displays due to their superior energy efficiency, longer lifetime, versatility, and other advantages. Lately, the revival of metal halide perovskites, with a common formula $ABX3$ (A representing a monovalent organic cation like formamidinium (FA), methylammonium (MA), or an inorganic cation B, $Cs+$ representing a metallic cation like $Sn2+$ or $Pb2+$, and X representing a halide anion such as $Cl-$, $Br-$, or $I-$), has led to the emergence of a fresh line of LEDs [5].

The appealing optical and electrical characteristics of organic-inorganic perovskites have garnered significant interest [6]. In particular, all-inorganic perovskite materials have captivated researchers due to their exceptional carrier mobility, efficient radiation recombination, excellent color purity, and adjustable bandgap [2]. These materials hold great promise as potential candidates for the development of next-generation LED technology [7].

All-inorganic perovskite compositions, such as $CsPbBr3$, exhibit superior thermal stability when compared to materials featuring a hybrid mix of organic and inorganic perovskite. The inorganic perovskites, such as $CsPbX3$ (with X = Cl, Br, and I), as well as hybrid halide systems like Cl/B and Cl/Br , have been found to possess enhanced thermal stability [8-10]. Furthermore, the remarkable properties of all-inorganic perovskites, such as their ability to emit narrowband light with a full-width at half-maximum (FWHM) < 20 nm, impressive external quantum efficiency (EQE) ,current efficiency (CE), high photoluminescence quantum yield (PLQY), efficient carrier diffusion , low rates of nonradiative recombination, and wide range of tunable wavelengths 400 to 700 nm have generated significant enthusiasm for the advancement of LEDs [11-13].

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*Corresponding author: Raheleh Zarei; Email: zarei.rahele@yahoo.com

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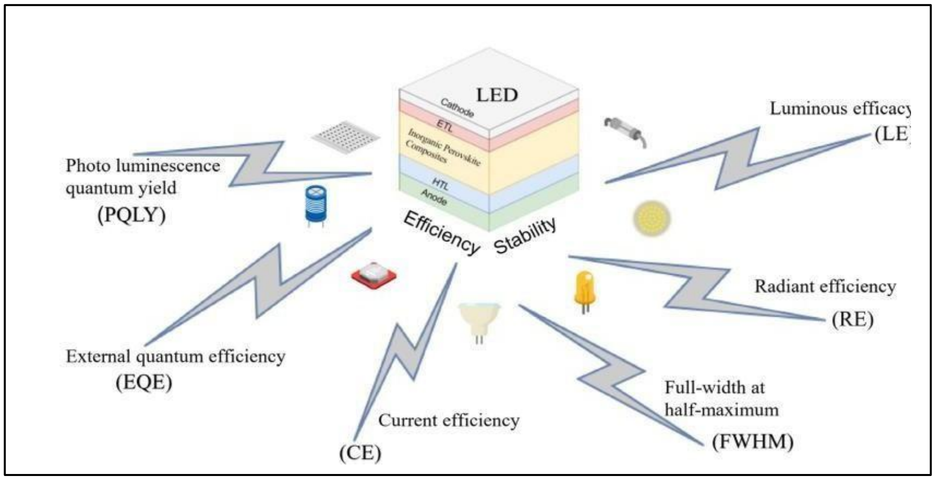

Fig.1. Remarkable properties of perovskites-LED

Nevertheless, the photoluminescence of the inorganic perovskite CsPbBr3 was relatively feeble, as observed in large single crystals [14, 15]. However, by incorporating nanocrystals of CsPbBr3 into optically inactive Cs4PbBr6 [16], the efficiency of light emission could be significantly improved. This enhancement can be primarily attributed to surface passivation, the spatial confinement of CsPbBr3 nanocrystals and interfacial emissive states [17].

The improved efficiency of radiative recombination when subjected to optical excitation can potentially result in an enhanced electroluminescence effect when incorporated into LED devices [18]. Apart from the recombination of charge carriers, the behavior of charge transport behaves is also essential in influencing the efficiency of LEDs. Previous studies have demonstrated that optimizing the CsPbBr3 | Cs4PbBr6 composite perovskite layer can effectively address the issue of inefficient charge carrier injection by adjusting the thickness and ratio of the layer [19, 20].

The evaluation of devices utilizing pure and composite perovskites indicated that the incorporation of composites could serve as a viable strategy to enhance the luminosity, efficacy, and durability of perovskite-based LEDs [18].

Inorganic perovskite composites are being recognized as a hopeful substance for LEDs because of their distinctive characteristics, including high color purity, tunable bandgap, excellent charge transport properties, and high PQ efficiency [21]. This paper presents the use of inorganic perovskite composites for LED applications, highlighting their potential for achieving high efficiency and stability. This study showcases techniques of synthesis inorganic perovskite composites, providing a comprehensive understanding of their optoelectronic properties and device performance. Furthermore, the paper addresses the stability challenges associated with inorganic perovskite composites, proposing innovative strategies to enhance their long-term performance and reliability.

Table 1.
Relationship between light energy, light wavelength, and LED color.

Light color		λ (nm)	Energy (Ev)
Violet	🟪	400-450	3.1-4.4
Blue	🟦	450-500	2.5-3.7
Green	🟩	500-750	1.9-4
Yellow	🟨	570-590	2.1-2.2
Orange	🟧	610-760	2-2.1
Red	🟥	610-760	1.6–2.0

2. Perovskite-Based LED

The EQE serves as a measure to estimate the efficiency of LEDs. The determination of the LED's efficiency is achieved through the calculation of the ratio between the number of photons emitted by the LED and the number of injected electrons.Eq (1) [22, 23]can be used to express the EQE.

$$\mathrm{EQE}=(\text{Number of emitted photons })/(\text{Number of the supplied electorns})=\gamma\times\chi\times\eta\_PL\times\eta\_oc \qquad \text{(Eq. 1)}$$

Achieving high-performance PeLEDs requires the creation of perovskite-emitting layers that exhibit a high PLQY. The PLQY is impacted by multiple variables, such as the proportion of excitons with spin-allowed optical transitions (χ) and the percentage of injected electrons that generate excitons (γ) and the out-coupling efficiency (ηPL). It's important to mention that the effectiveness of LEDs, as measured by EQE, is typically directly proportional to PLQY of layered perovskite. Therefore, enhancing the PLQY of perovskite-emitting layers is crucial for achieving efficient and high-performance PeLEDs [23].

PLQY is the proportion of emitted photons to absorbed ones [2]. For a LED, wall plug efficiency (WPE) or radiant efficiency (RE) refers to the efficiency of converting electrical energy to optical energy and can be defined as:

$$\text{RE or WPE}= \mathrm{EQE}\times\mathrm{LE} = \eta\ \text{injection}\times\mathrm{IQE}\times\eta\ \text{extraction}\times L/(I\times V) \qquad \text{(Eq. 2)}$$

In this context, the EQE is determined by comparing the number of emitted photons to the quantity of electrons injected into the device. The ratio of electrons injected into the active emitter layer to the total number of electrons flowing through the deviceis denoted as η injection. The internal quantum efficiency (IQE) represents the percentage of electron-hole recombination events in the emitter layer that result in the emission of light, as indicated by references [24]. On the other hand, η extraction refers to the percentage of photons produced in the emitter layer that effectively exits the device [25]. Finaly, the luminous efficacy (LE) is the proportion of the emitted light to the injected energy provided by the source [26]. The summary of the notable properties of perovskites can be seen in Figure 1. LEDs have been developed with different wavelengths, including infrared, visible, and ultraviolet (UV).

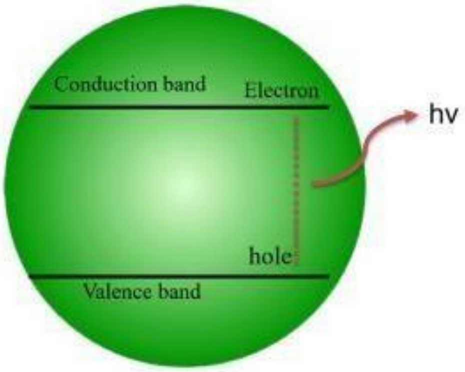

Fig. 2. The process of electron transitioning from the conduction band to the valence band and scattering a photon. If the wavelength of the emitted photon falls within the visible region, the resulting light is colorful. hν = hc/λ, ν = light frequency, h = Planck's constant, c = light speed, and λ = light wavelength.

LEDs have been developed with different wavelengths, including infrared, visible, and ultraviolet (UV). These LEDs can emit light at various levels, categorized as low, intermediate, or high light emission. When an electric current flows through an LED, it causes the semiconductor device to emit light. The release of photons in the form of energy is a result of the recombination of holes and electrons within the semiconductor material, leading to the emission of light (as shown in Figure 2). The emitted light color from LEDs is directly related to the energy of the photons released, which is determined by the semiconductor's band gap. This information is summarized in Table 1.

The high values of luminescence quantum efficiency serve as evidence for the successful conversion of electrical energy into light, leading to reduced energy consumption and improved performance of LEDs. Perovskites play a crucial role in photoelectric applications due to their exceptional efficiency values. By modifying the structure and chemical composition of perovskites, it becomes feasible to adjust their band gap, thereby enabling control over the emitted wavelength. Consequently, the colors emitted in LEDs can be finely tuned [27].

3. Properties and Types of inorganic Perovskite LED

Inorganic perovskites exhibit several unique properties that make them attractive for various applications, including LEDs. Some of these properties are:Optoelectronic Properties, bandgap Tunability,high Charge Carrier Mobility,stability . Inorganic perovskites have excellent light-absorbing and emitting properties. They possess a high absorption coefficient, enabling efficient light absorption even with thin layers of the material. The composition of the elements can be altered to adjust the bandgap of inorganic perovskites. . This allows the emission wavelength of the material to be precisely controlled, making them suitable for different applications, including LEDs with various colors. They typically exhibit higher charge carrier mobility compared to organic materials. This leads to improved electrical conductivity and device performance.They are often more stable than their organic counterparts, especially against moisture and heat. This enhanced stability is desirable for long-term device operation and reliability.These LEDs have gained attention due to their potential for high efficiency and stability. In the following sections, the most important types of inorganic perovskites- LED have been discussed.

3.1 Three-dimensional bulk structure

Perovskites are a group of compounds characterized by their three-dimensional structural framework, denoted by the chemical formula AMX3 [28]. The A-site within this framework can be occupied by either Inorganic metal cations with a single valence such as Rb+ or Cs+ , or organic cations like MA+ or FA+. On the other hand, the M-site is typically filled by divalent metal cations, predominantly Pb2+, however, it is also capable of accommodating various other cations. such as Sn2+, Eu2+, Cu2+, Ni2+, and so on. X represents a halide anion, which can be either Cl−, Br−, or I−. Within the perovskite crystal structure, the M cation is positioned at the cube center, whereas the X anions and A cations are situated at face centers and the vertexes of the cube, respectively [29, 30].

The PbX6 configuration creates regular octahedra through the central M cation (e.g., Pb2+) and the six halide anions that surround it [31]. This arrangement creates an ideal 3D cubic phase perovskite structure) Figure 3(, where the PbX6 octahedra share corners in a continuous array. However, if the PbX6 octahedra are not in perfect cubic alignment, the perovskites adopt a less symmetrical orthorhombic form, as illustrated in Figure 3.

Perovskites exhibit further categorization into two types: organic/inorganic materials, like MAPbX3 and FAPbX3, and all-inorganic perovskites such as CsPbX3 [32]. The initial demonstration of a PeLED, pioneered by Tan et al. [33], The experiment utilized an infrared gadget that produced light at 750 nm through electroluminescence (EL). This gadget was constructed using 3D bulk MAPbI3−xClx as the emitting substance. The PeLED demonstrated a peak EQE of 0.76% and an infrared radiance of 13 W sr−1 m−2. Notably, in this LED configuration, the perovskite material exists in the form of a bulk crystal.

The structure of perovskite crystals is composed of interconnected networks of metal cations, halide anions, and various other elements [34]. Typically, these three-dimensional perovskite LEDs showcase remarkable optoelectronic characteristics, such as exceptional quantum efficiency and color purity. They have shown great potential in terms of brightness and efficiency. Nevertheless, a significant hurdle faced by 3D perovskites is their long-term stability, particularly when exposed to moisture [35].

3.2 Inorganic perovskite nanocrystals

Another form of inorganic Perovskite LED employs perovskite nanocrystals or quantum dots (QDs). These nanoscale crystals possess a perovskite structure and display optical properties that vary with their size. Consequently, the color produced by these nanoparticles' emission can be adjusted by manipulating their size [36, 37].

Perovskite QD light-emitting diodes (LEDs) present several benefits, including superior color purity, narrow emission line widths, and the ability to be processed in solution [38]. These LEDs have demonstrated potential in achieving both efficient and stable light emission. Furthermore, the nanocrystal structure of perovskite QDs offers enhanced stability when compared to three-dimensional perovskites [39].

Inorganic nanocrystals based on 0D perovskites, specifically colloidal CsPbX3 (where X = I, Br, and Cl), have appeared as a promising group of materials for light emission. These nanocrystals are synthesized by a reaction between cesium carbonate and oleic acid in a metal halide solution. Notably, Loredana Protesescu et al. [40] were the first to successfully develop the CsPbX3 structure, which exhibits highly adjustable optical properties and a high PLQY Colloidal perovskite CsPbX3 NCs have adjustable bandgap energies that cover the visible spectrum and emit bright light. The properties of these NCs were observed in toluene under a UV lamp, with different stimulation wavelengths and time-resolved PL decays

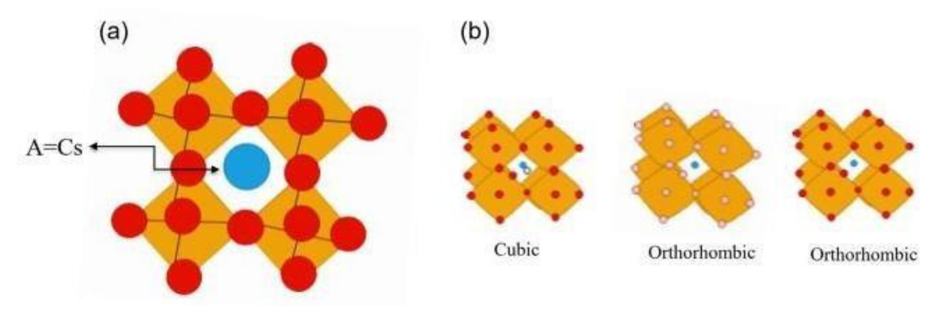

Fig. 3. (a) AMX3 (A=Cs) inorganic perovskite ,(b) Cubic (MAPbBr3), Orthorhombic (CsPbI3 ,CsPbB3)

shown in Figure .4. It is important to mention that the smaller-sized nanocrystals demonstrate an increased exciton binding energy, making the photoluminescence emission more likely to occur through exciton recombination rather than bimolecular recombination of free carriers [41].

The emission wavelength of all-inorganic CsPbX3 QDs has been adjusted within the range of 410 to 700 nm [42]. Additionally, impressive photoluminescence quantum yields (PLQYs) ranging from 50% to 90% have been attained. By manipulating the size of perovskite NCs, the emission color can also be regulated through the utilization of the quantum confinement effect. This effect is accompanied by an improved PLQY, which is likely due to the significant exciton binding energy and well-maintained confinement of charge carriers [43].

Table 2. Summary of norganic perovskite NCs in recent years

Perovskite	EL (nm)	EQEmax (%)	CE^{max} (cd A^{-1})	Lmax(cd m^{-2})	PLQY (%)	Year	Ref.
$CsPbBr_3$	520	1.3	5.2	54	-	2018	[44]
$CsPbBr_3$	-	1.70	5.57	1562	-	2018	[45]
δ-$CsPbI_3$	682	8.65	-	210	-	2018	[46]
$CsPbBr_3$	515	11.6	45.5	55800	61	2018	[50]
$CsPbI_3$	692	8.2	0.8	827	-	2019	[51]
CsPbBr	520	8.2	25.7	500	up to 87	2019	[47]
CsPbBr	517	9.7	31.7	2270	-	2019	[52]
$CsPbI_3$	671	10.3	-	823	84-89	2019	[53]
$CsPbBr_3$	512	12	39.3	7657	38	2019	[54]
$CsPbI_3$	689	1.25	-	468	95	2020	[55]
$CsPbI_3$	693	10.6	-	981	51	2020	[56]
$CsPbI_3$	630	6.4	-	-	-	2021	[57]
$CsPbBr_xI_{3-x}$	659	8.94	-	2859	15.3	2021	[58]
$CsPbBr_3$	522	16.45		112 824		2021	[59]
$CsPbBr_3$	-	19.3	-	1946	-	2021	[60]
$CsPbX_3$	-	21.4	-	2000	60.0-87.0	2021	[61]
$CsPbI_3$	640	23	-	200	-	2021	[62]
$CsPbI_3$	682	8.15	-	584	72.9- 94.3	2022	[63]
$CsPbBr_3$	534	11.19	51.0	20388	-	2022	[64]
$CsPbI_3$	695	13.8	10.8	7039	73.0 - 59.2	2022	[65]
$CsPbI_3$	514	20.79	65.68	584	96.02%	2023	[48]
$CsPbI_3$	-	20.65	-	3861	-	2023	[66]
$CsPbI_3$	688	22.8	-	15204	93	2023	[49]
$CsPbI_3$	664	23	-	-	90	2023	[67]

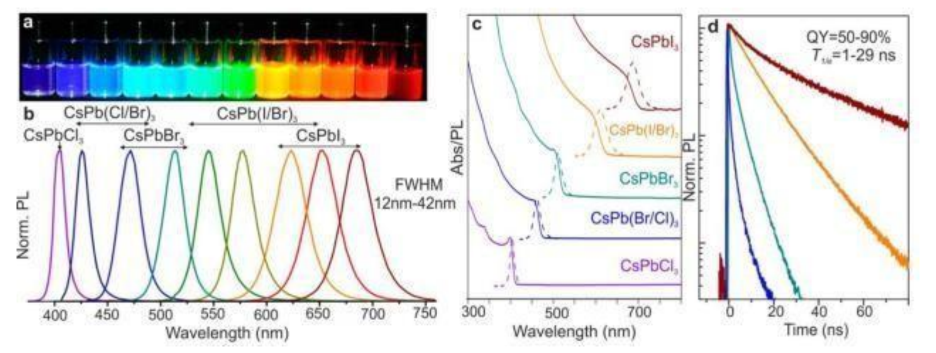

Fig. 4. (a) observation of bright emission in toluene colloidal solutions under a UV lamp (λ = 365 nm); (b) presentation of representative photoluminescence (PL) spectra with excitation at 400 nm (except for CsPbCl3 samples, which are excited at 350 nm); (c) display of usual PL spectra and optical absorption; and (d) examination of time-dependent PL decay rates for each sample, excluding CsPbCl3 [40].

In 2018, Naresh Kumar et al. [44] introduced a novel approach to enhance the efficiency of PeLEDs. They utilized high-quality green emissive colloidal CsPbBr3 NCs with an average size of 11±0.7 nm. The steady-state photoluminescence (PL) and EL, with FWHM fell within the interval of 20±0.5 nm, indicating a remarkable feature of high color purity in these materials, making them suitable for achieving a wider color gamut.To further optimize the performance of the CsPbBr3 NCs, the researchers treated a 4-layer film of these nanocrystals with MeOAc. This treatment resulted in a maximum luminance efficiency of approximately 5.2 cd/A, with a mean efficiency of 2.32 cd/A across six devices. Additionally, the electroluminescent quantum efficiency (EQE) reached approximately 1.3% at 6.5 V.

In their study, Lin Wang et al. [45] have founded a simple yet effective approach called solvent-assisted surface engineering to enhance the quality of nanocrystal thin films for LED application. By employing solvents of varying polarities, they successfully obtained assemblies of CsPbBr3 nanocrystals. The efficacy of their strategy was further confirmed through the successful production of CsPbBr3 LEDs , which exhibited exceptional efficiency. As a result, a significant 34-fold increase in EQE (reaching up to 1.70%) was accomplished in CsPbBr3 LEDs fabricated using solution processing. Furthermore, Boning Han et al. [46] have reported a promising approach to manipulate phases in CsPbI3. This involves introducing a long-chain cation such as naphthalene-1-yl ethanamine (NEA) to create stable and high-performing red LEDs based on CsPbI3. The study showcases an impressive EQE of 8.65% for the distinct red light emission around ≈682 nm, marking the highest value reported for Cs-based red PeLEDs up to now. Additionally, the PeLEDs show exceptional stability, with The EQE stays maintained at 90% following 3 months of storage [46]. In another research, researchers successfully synthesized monodisperse CsPbBr3 nanorods with adjustable the ratio of the span and a pristine surface by converting Cs4PbBr6 nanocrystals at the interface. The process of formation was thoroughly investigated. These nanorods exhibited remarkable photophysical properties, such as PLQY reaching 87% and a photoluminescence lifetime of 44 ns. Analysis using ultraviolet photoelectron spectroscopy revealed that CsPbBr3 nanorods have an elevated valence band peak than nanocubes, suggesting a more effective hole injection rate beneficial for LED applications. To demonstrate the potential of CsPbBr3 nanorods, a prototype LED was constructed utilizing them as a green light source. Remarkably, the LEDs achieved the EQE of over 8.2% without the need for laborious cleaning steps. This performance is among the best reported for LEDs based on CsPbBr3 nanocrystals thus far [47].

The effective reduction of defect formation energy in PNCs is achieved by introducing metal acetate salts. The resulting PNCs exhibit exceptional characteristics such as near-perfect photoluminescence quantum yield, remarkable stability, luminance of 1175 cd m−2, CE of 65.48 cd A−1, EQE of 20.79%, and a wavelength of 514 nm in optimized PNC LEDs. These desirable properties are attributed to the presence of a Cd2+ passivator and DDA ligand [48].

In a separate study conducted by Po Lu et al. [49], they utilized a typical triphenylphosphine (TPP) ligand to investigate its impact on the surface of CsPbI3 perovskites NCs. Additionally, the incorporation of extra benzene rings in the form of 2-(Diphenylphosphino)-biphenyl (DPB) enhanced the delocalized characteristics of the PNC surface and significantly improved the charge transport within the PNCs. Consequently, the DPB passivated CsPbI3 NCs demonstrated top-emitting LEDs with remarkable performance metrics, including an exceptionally low-efficiency roll-off of 2.6% at a current density of 500 mA cm−2 and a peak of 22.8%, a maximum luminance of 15,204 cd m−2.Table 2 summarizes the performance of PeLEDs using various types of perovskite nanocrystals and all-inorganic perovskite materials.

4. Inorganic composite Perovskite LED

Inorganic composite Perovskite LEDs represent a cutting-edge technology in the field of lighting and display applications. These LEDs utilize a unique combination of inorganic materials with Perovskite structures to achieve enhanced performance and efficiency. Perovskite materials, known for their excellent optoelectronic properties, have attracted a lot of focus lately because of their exceptional light emission efficiencytunable bandgap, and cost-effective fabrication processes. By incorporating these materials into inorganic composite structures, researchers aim to overcome some of the challenges associated with pure organic or inorganic LEDs.One of the key advantages of inorganic composite Perovskite LEDs is their improved stability and lifespan compared to traditional organic LEDs. The inorganic components help enhance the material's resistance to environmental factors such as moisture and oxygen, leading to longer-lasting and more reliable devices.

4.1 Synthesis methods of inorganic-based Perovskite LED

The synthesis techniques for inorganic-based composite Perovskite LED involve combining various inorganic materials to create a highly efficient and versatile light-emitting device. In the past few years, there has been considerable interest in the composite Perovskite LEDs because of their promise for application in advanced lighting and display technologies.Figure 5 illustrates a summary of the synthesis methods for these perovskites.

4.1.1 Hot-injection

One approach that is frequently used for manufacturing perovskite materials is the hot-injection method. By using this technique, different halide compositions, sizes, and forms can be created. The NCs grow extremely quickly, and while reaction time is mostly responsible for determining average size, it is more practical to reduce reaction temperature than growth time. By adjusting the precursor salt ratios, mixed-halide can be produced easily. The band gap and emissions can be adjusted by halide and size modulations [68]. The schematic of the method hot-injection is shown in Figure 6. Novel composites of CsPbX3@mica with excellent thermal and light radiation stability have been successfully created through the hot injection strategy by Yanxia Yu et al. [69]. Jinyang Zhu et al. [70] demonstrated perovskite quantum dots (QDs) stability is often compromised, along with the rapid Reaction involving the exchange of anions that occurs among various halide ions. To address this issue, they incorporated red light-emitting CsPb(Br/I)3 QDs and green light-emitting CsPbBr3 QDs into carboxyl-mediated polymethyl methacrylate (PMMA) using the hot-injection method. Consequently, the resulting PMMA/perovskite composites not only maintain a high level of luminescence but also demonstrate excellent resistance to water. Additionally, this treatment effectively prevents the exchange of anions between different halide QD particles when in a solid state. All-inorganic perovskite NCs have gained attention as a viable substitute for hybrid organic-inorganic perovskite in optoelectronic applications due to their distinct electrical and optical characteristics, as well as enhanced chemical stability. The introduction of metal or metal nanoparticles into these all-inorganic perovskite NCs through doping allows for the modification or adjustment of their optical characteristics. In another paper , Ag-CsPbBr3 nanocrystals were successfully synthesized using the hot injection method [71].

4.1.2 Room temperature synthesis

The method of creating perovskite crystals at room temperature, usually between 20 and 25 degrees Celsius, is referred to as room-temperature synthesis of perovskite materials. Numerous benefits, including easier reaction conditions and less consumption of energy, come with this method. There are alternate methods that enable room-temperature synthesis in addition to the conventional hot-injection technique that has already been described for perovskite synthesis. Although polar solvents are frequently employed to prepare precursor solutions by injection method, the solvents utilized in room-temperature synthesis methods are typically low polarity or non-polar solvents, such as toluene or chlorobenzene. It's crucial to keep the area dry while mixing the precursor solutions using either method [16]. Li et al. [72] were the pioneers in showcasing the application of a room temperature supersaturated recrystallization technique for creating CsPbX3 nanocrystals.

Mo Qionghu et al. [73] showed the PLQY of CsPbBr3@SiO2 quantum dots (QDs) achieved a remarkable value of 71.6%, whereas it was only 46% for pure CsPbBr3 QDs. Furthermore, the CsPbBr3@SiO2 QDs displayed exceptional stability when subjected to heat. Additionally, an improved two-photon pumped amplified spontaneous emission (ASE) was successfully demonstrated under normal air conditions. Comparatively, the ASE threshold of CsPbBr3@SiO2 QDs films was reduced by 70 μJ/cm2 when compared to those employing CsPbBr3 QDs, utilizing a laser excitation powered by two-photon. As depicted in the shematic presented in Figure 1a, it can be observed the synthetic process was carried out in two steps by Ludan Zhu ete al [74]. Firstly, CsPbBr3 nanocrystals were formed, followed by size control through the addition of APTES. The Experimental section provides a comprehensive account of the process. Notably, the sol sample exhibited a vivid green color when exposed to ultraviolet light at a wavelength of 395 nm (Figure 7c). Furthermore, the utilization of an ultraviolet polymerization method enables the preparation of CsPbBr3 nanocrystals/polyarcylic composites (Figure 7b,c).

4.1.3 Ultrasonication

In recent years, the preparation of NP has been documented through the utilization of direct ultrasonication technique, along with the solvent-free mechanical synthesis approach. These methods offer a straightforward, scalable, and efficient approach to synthesizing high-quality colloidal CsPbX3 (X = I, Br, and Cl) perovskite NCs. Notably, this synthesis approach allows for the control of the composition of halide ions and the precursor solutions thickness, all while eliminating the need for polar solvents and incorporating organic capping molecules [37]. Using high-frequency sound waves, usually ranging from 20 to 100 kHz, on a liquid medium that contains the precursor components is referred to as ultrasonication. Ultrasonication can be employed in the production of perovskite materials to optimize reaction kinetics, regulate the dimensions and structure of the resulting perovskite nanoparticles, and increase precursor material dispersion. Colloidal inorganic perovskite nanocrystals, specifically CsPbBr3, exhibit remarkable optoelectronic properties and enhanced stability compared to their hybrid counterparts. Nevertheless, the efficiency of blue-emitting CsPbBr3 nanocrystals is still inferior to that of their green counterparts. Moreover, their production usually necessitates elevated temperatures and the use of an inert gas atmosphere. To address these challenges, Xiaoli Xu et al. [75] Suggest a top-down method for the effective production of blue-emitting CsPbBr3 quantum dots in a normal air environment. This technique includes breaking down CsPbBr3 nanoplatelets (NPLs) into spherical QDs through ultrasonication and treatment with hydrobromic acid (HBr). The produced CsPbBr3 QDs show outstanding uniformity, with an average size of around 5 nm, and emit blue light with a wavelength of 460 nm." Furthermore, they demonstrate a high PLQY of 53.2%. This work represents a significant advancement towards achieving the desired synthesis of perovskite NCs with efficient blue emission in air environment. Shematic this method dementrated in figure 8.

4.1.4 Vapor deposition technique

Without using solvents, perovskites are made using solid-state techniques. This technique has the advantages of solvent-free, being reasonably straightforward, and economical [76, 77].

Using a vapor deposition technique, Ling Yet al. [78] created CsPbBr3/Cs4PbBr6 composites for improved photoluminescence (PL). Dual-source thermal evaporation offers an opportunity to tune the concentration of the component materials in a wide range, which is crucial for understanding the luminous behaviors in these composites. This process is superior to solution synthesis in this regard. Regardless of the ratio between the two phases, the composite films made using this technique have low pinhole-free morphology and surface roughness. Insufficient film coverage and high surface roughness are frequently caused by the low solubility of Cs precursors in solution synthesis (for example, CsBr in the polar solvent) [79, 80].

Efficiency variations can result from different synthesizing techniques. When comparing co evaporated composite thin films to solution-synthesized composite NCs, the PLQY of the second type shows a monotonic increase with increasing Cs4PbBr6 concentration. Due to the interfacial states between the two phases, which contribute to the concentration-dependent PLQY, these variances suggest that alternative preparation techniques can result in varied light emission behaviors. The CsPbBr3/Cs4PbBr6 grain boundaries likely generate a type of shallow trap states in this case that have not yet been seen in halide perovskites and are the cause of the PL increase seen. According to their findings, composites with purposefully created heterogeneous interfaces present new opportunities for researching and enhancing the material's properties and capabilities [78].

Large quantities of materials cannot be obtained by a simple and scalable precipitation synthesis approach. This is due to the fact that conventional methods, such as large organic group confinement crystallization or solvent-induced co precipitation, require several of processing, separation, and precise crystal thickness control [81].

4.1.5 Others

The adaptability of perovskite nanoparticles is demonstrated by the wide range of factors that can be altered to change their electronic and optical characteristics, such as chemical composition, structure, and particle size. By accurately controlling experimental parameters like the precursor duration, reaction temperature, concentration, and chemical composition, it is possible to tailor the morphology, optical and electronic properties of perovskite nanoparticles with ease. Another various methods have been demonstrated for synthesizing colloidal perovskite NPs, including

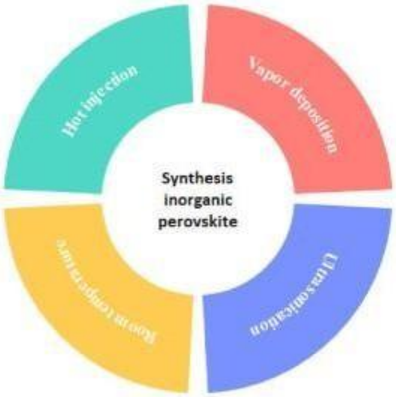

Fig. 5. Main synthesis methods of inorganic Perovskite LED

solvent-induced precipitation, ligand-assisted reprecipitation (LARP), emulsion processes, template-assisted synthesis, and novel synthesis [82, 83]. The dissatisfactory stability of lead halide perovskites, because of their delicate ionic crystal attributes and continually dynamic surface-coordinated states, has limited their applications. However, researchers have discovered that in-situ diphase structure passivation, involving the application of identical chemical components to protect the perovskites (e.g., passivating CsPbBr3 with Cs4PbBr6), can effectively improve their stabilities while maintaining their high-efficient luminescence properties. In a groundbreaking study, the researchers introduce a novel anion-cation reaction method to synthesize lead halide perovskite nanocrystals with a diphase CsPbBr3/Cs4PbBr6 structure. Additionally, they observe that the phase transformation between CsPbBr3 and Cs4PbBr6 is temperature-dependent [84].

4.2 Properties inorganic-based composite perovskite LED

Researchers have suggested numerous solutions to enhance the stability of PeLEDs. Creating a core/shell grain configuration, where 3D bulk grains are enveloped by a shell layer like bulk organic cations, could be a more effective approach to enhance the longevity of PELEDs. This method involves encapsulating the grains with a protective shell, which effectively passivates the grain boundaries in all directions, thereby impeding ion migration [85].

Hu et al. [86] successfully synthesized CsPbBr3–Cs4PbBr6 microcrystals, which exhibit a unique composite structure. These microcrystals demonstrate remarkable luminescent properties and exhibit good stability. Notably, the photoluminescence (PL) intensity of these microcrystals only decreases by 20% after being exposed to ambient conditions for a period of 2 months.

The Cs4PbBr6 phase was introduced by Akkerman et al. [87], who also incorporated nanocrystals of CsPbBr3 within the photoactive Cs4PbBr6 to create a core-shell structure known as Cs4PbBr6/CsPbBr3. In this structure, the electrons and holes generated in CsPbBr3 are confined spatially by Cs4PbBr6, leading to a notable enhancement in the luminescence efficiency.

A study on the effects of CsPbBr3 and Cs4PbBr6 on the improvement of PL in composites was undertaken by Ling Y and his colleagues [78]. They discovered that the composites' single light emitter was CsPbBr3 by varying the material composition over a large range. Surprisingly, the addition of Cs4PbBr6 greatly increased the light emission efficiency in the composites despite the fact that it lacked PL characteristics.

As the quantity of CsPbBr3 decreased in the films, the PL intensity showed an increase.By passivating grain boundaries with luminous shallow states, the inactive Cs4PbBr6, in the form of a host-guest system with CsPbBr3 crystallites, was essential in improving the PL processes. By measuring the PLQY with an integrating sphere, it was determined that the efficiency of PL improved as the concentration of Cs4PbBr6 in the composite thin films increased. Due to the poor sensitivity of XRD in detecting minute levels of luminous components, some materials, notably those dominated by Cs4PbBr6, may have been mistakenly identified as luminescent in the past. These findings give designers of composite perovskite materials important information for achieving the best possible light emission performance [87, 88].

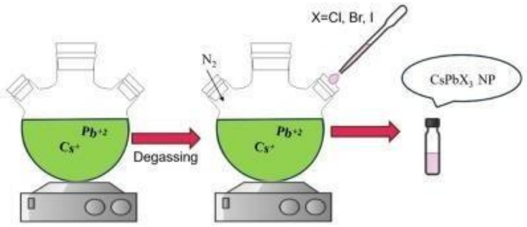

Fig. 6. Hot-injection method

In another study, high PLQY and narrow full-width at half-maximum (FWHM), green CsPbBr3 perovskite nanocrystals are thought to be a potential luminous material for next-generation lighting and displays. Due to their varied electrical structure, zero dimensional Cs4PbBr6 perovskite nanocrystals have also been described and created. They are unable to exhibit excitonic and absorption emission in the visible spectrum because of their band gap width exceeding 3.2 eV. [87]. For the purpose of spreading the CsPbBr3 nanocrystals and creating dual phase CsPbBr3 - Cs4PbBr6 (DP-CPB) composites that emit a bright green light, Cs4PbBr6 can act as the framework [88]. The DP-CPB perovskite composites have good solid state luminous performance and the PLQY can reach 95% when compared to the CsPbBr3 perovskite solid (PLQY 0.1%) [88].

Hongting Chen et al. [54] in their research found utilization of NaBr in CsPbBr3 NPs green LEDs results in a significant improvement in their external quantum efficiency (EQEmax), reaching a remarkable value of 17.4%. This enhancement is evident when compared to the EQEmax of LEDs that do not incorporate NaBr, which stands at 12%. Moreover, even when considering a larger area of 108 mm2, the NaBr-based CsPbBr3 NPs LEDs maintain a commendable maximum EQE of 10.2%. Moreover, to leverage the combined benefits of PEA and PEO, CsPbBr3 nanoparticles were synthesized in situ, resulting in an average grain size of 32.4 nm. The CsPbBr3 nanoparticles LEDs fabricated this way achieved a peak EQE of 12%.

5. Strategies for improved properties of perovskites suitable for LED applications

In recent years, Perovskite LEDs have undergone accelerated development and currently, the EQEs of perovskite LEDs is more than 23%. Among the factors that limit the practical use of such devices are the low efficiency of blue-emitting devices, short device lifetimes, insufficient knowledge about how the electric field impacts mobile ions within perovskite materials, a reduction in external quantum efficiency under high current density, and challenges in reaching emission wavelengths beyond 800 nm. [5, 101-103].

Several strategies have been recommended to resolve these problems, such as utilizing stable perovskite materials, optimizing

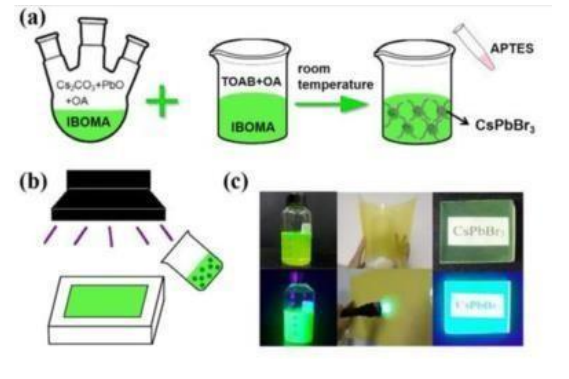

Fig. 7. (a) The synthesis process of CsPbBr3 nanocrystals sol is conducted in-situ using a one-step method, (b) solid composites of CsPbBr3 nanocrystals are prepared, (c) nanocrystals sol [74].

of device structures, and the introduction of new fabrication methods. Lessons learned from perovskite solar cells and organic LEDs can be applied to improve the stability and efficiency of perovskite LEDs as well [104, 105].

Perovskite LEDs possess the potential for use in a range of optoelectronic functions. They promise electroluminescent that is both cost-effective and high-performing. Perovskite LEDs with long-term stability and high efficiency will rapidly increase their practical applicability. Additional study is required to overcome the obstacles and enhance the stability and efficiency of perovskite LEDs [106]. In the ultraviolet portion of the electromagnetic spectrum, Perovskite materials commonly emit in the so-called UVA region 320 to 400nm — a range suitable for UV curing and other applications. UV curing is an extensively used, low-cost industrial technique for drying inks, adhesives, and coatings with intense UV light [107-109]. UV light-sensitive materials that contain photo initiator molecules, when exposed to UV light, activation energy is provided to start the reaction. As the chemical reaction initiates, the liquid rapidly solidifies by cross-linking with oligomer and monomer molecules. Although UV-emitting perovskite emitters have been presented, they have not yet been incorporated into LEDs [110]. Due to the necessity of UV radiation of a shorter wavelength ,200 to 280 nm UVC for such applications, the perovskite emitters devised so far are inadequate for applications like purifying drinking water, treating microorganisms, and creating disinfectant. The most significant applications for perovskite LEDs in the range of visible are augmented/virtual reality, high-brightness applications such as solid-state illumination and projection screens, and in display devices. Perovskite LEDs offer numerous benefits as display technology transitions to active-matrix organic LEDs (AMOLED) from liquid-crystal displays. Their easy processing allows seamless integration on thin-film transistor backplanes, enhancing display resolution, brightness, and color gamut. Perovskite emitters, known for superior color accuracy, have the potential to deliver higher resolution. Perovskite materials can be processed on flexible substrates and at low temperatures. Thus, they are ideal options for flexible displays. Particularly, display devices, such as AMOLED-based devices, are manufactured using lithography patterning, a widely used and industrially compatible technique. Lately, perovskite materials have shown compatibility with lithography patterning, enabling size reduction within the 1 to10 μm range [111, 112].

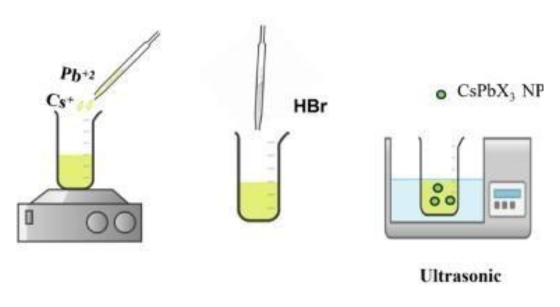

Fig. 6. Ultrasonication method

To prevent the deterioration of perovskite films during liftoff, which often involves high-polarity solvents, researchers have shown that a dry-liftoff method using mechanical peeling of the photoresist material is efficient [111]. In solid-state lighting uses like projection displays, stage lights, indicators, automobiles, decoration, interior lighting and so on, high power efficiency is required. LEDs with a power efficiency ranging from 40 to 100 lm W-1 are deemed suitable for solid-state lighting, despite the absence of a clearly defined threshold. In 2017, the luminous efficacy of high-brightness, cutting-edge LEDs made from inorganic materials approached 160 lm W-1 [113], and this increased to 200 lm W-1. A higher lumens-per-watt ratio signifies better energy efficiency, which is the desired characteristic in LEDs. Perovskite LEDs have shown a luminous efficacy greater than 120 lm W-1 [114]. Even though this is still far below the theoretical upper limit of an optimal white-light source (414 lm W-1) [113], there is no basic restriction on the luminous efficacy of Perovskite LEDs.

Perovskite LEDs are also potential for NIR applications [115] including optical switches, telecommunication, and night vision. Here, the specific application is determined by the emission wavelength in the NIR range (700–2,500 nm), such as their use in optical wireless communication and vivo bio imaging, biomedical sensing. Perovskites-based LEDs continue to outshine their NCs counterpart. In 2015, for instance, green-emitting LEDs withe the CE of 42.9 CdA-1 were demonstrated using hybrid organic-inorganic perovskites [116]. Nonetheless, since their synthesis has been reported, inorganic (CsPbBr3) perovskite NCs-based LEDs have demonstrated a remarkable performance boost.

Actually, the initial green-emitting CsPbBr3 NC LED showcased a current efficiency of 0.43 CdA-1 [117], and in less than a year, LEDs of this type have reached 13.3 CdA-1 [118] in the same spectral range. Due to the expertise gained in the last twenty years in producing LEDs with solution-processed materials, performance is rapidly improving. In fact, the majority of the manufacturing methods utilized in organic (OLEDs) or II-VI and III-V semiconductor QD LEDs are entirely transferable, and a wide range of materials that are capable of being utilized as electrodes or charge transport layers are readily available today, thereby facilitating device optimization. Although there has been a swift enhancement in efficiency and luminance levels, the predominant findings are concentrated within the green spectrum ranging from 500 to 550 nm. In contrast, blue emitting perovskite NCs LEDs continue to trail in terms of efficiency and maximum luminance. In actuality, the stability and overall operational lifetime of perovskite NCs LEDs is a significant concern [117, 119].

Further investigation is needed to uncover the mechanisms of degradation that take place during LED operation, exposure to air, and storage. Previous studies have indicated that the use of mixed halides for color tuning leads to an unstable emission color within a few seconds of operation [119]. In 2014, Prieto and colleagues showcased the initial instance of perovskite nanocrystal LEDs

Composite	Method	Maximum luminance (Lmax)	luminous efficacy	PLQY	Main result	Ref
$CsPbBr_3$ @ SiO_2	Room temperature	-	-	71.6%	The PLQY of $CsPbBr_3@SiO_2$ quantum dots (QDs) achieved a remarkable value of 71.6%, whereas it was only 46% for pure CsPbBr3 QDs.	[73]
$Cs_4PbBr_6/CsPbBr_3$	Room-Temperature	-	-	48.78%	Synthesis of Cs4PbBr_6/$CsPbBr_3$ mixed crystals on a significant scale, resulting in a high PLQY of 48.78%. During environmental stability testing, it was observed that there was an approximate 20% decline when exposed to ambient conditions with 50% RH for a period of 2 months.	[86]
NaBr /$CsPbBr_3$	synergistic	8353	-	17.4%	The utilization of NaBr in CsPbBr3 NPs green LEDs results in a significant improvement in their external quantum efficiency (EQEmax), reaching a remarkable value of 17.4%. This enhancement is evident when compared to the EQEmax of LEDs that do not incorporate NaBr, which stands at 12%.	[54]
$CsPbBr_3$ @ SiO_2	all-solid-state process (sintering after grinding)	-	-	15.5%	A straightforward green method was fine-tuned for synthesis, achieving ultra-high stability without the use of solvents. The intensity was sustained at 100% even after undergoing a 196-hour test under harsh double-85 conditions.	[77]
hierarchical CaF_2 nanospheres loading $CsPbX_3$	Hydrothermal/mixing	-	2.7 lm W^{-1}	50, 82, and 66%	highly luminescent and stable CaF_2-PQDs nanocomposites	[89]
silica-coated $CsPbBr_3$ QD	sol–gel	-	63.5 lm W^{-1}	-	Enhanced material durability when exposed to light, heat,and environmental factors such as moisture and oxygen.	[90]
$CsPbBr_3$-Cs_4PbBr_6	single atomic supersaturated recrystallization method	-	-	40.8%	The synthesis process is simple and requires minimal energy, making it suitable for large-scale production and practical applications.	[91]
$CsPbX_3$@mica	hot injection strategy	-	-	38.5%	high thermal stability and light radiation stability	[69]
$CsPbX_3$@α-Al_2O_3	hot injection strategy /simple coating mechanism	-	86.58 lmW^{-1}	58%	The composite material that was created could produce adjustable emissions ranging from 430 to 636 nm.	[92]
$CsPbBr_3$–Cs4PbBr_6	chemical solution route without inert gas protection	-	45 lmW^{-1}	74%	The composite perovskite nanocrystals showed high quantum yield and distinct emission spectra, surpassing CsPbBr3 nanocrystals.	[93]
green $CsPbBr_3$@glass and red $CsPbBr_{1.5}I_{1.5}$@ glass composite	modulating perovskite concentration in glass and heat-treatment temperature	500 000 cd m^{-2}	-	94% and 78%	high PLQY, and excellent stability	[94]
Mn^{2+}-doped Cs–Pb–Cl	chemical solution route	-	-	77.3%	Improving optical performance ultimately through suppressing the nonradiative transition of the exciton	[95]
$CsPbBr_3$@ Cs_4PbBr_6	solid-state synthesis	-	-	>90%	Improving the overall stabilities of CsPbBr3 NCs against heat, moisture, and photoirradiation.	[96]
$CsPbBr_3$:Sr/ PbBr(OH)/	high-temperature solid-phase method	-	86 lmW^{-1}	75%	Strong resistance to heat and water, along with improved stability against the combined effects of blue lightand water, or blue light and heat, was observed.	[97]
$CsPbX_3$/SBA-15	in situ growth strategy	-	183 lmW$^{–1}$	-	Utilizing Mesoporous SBA-15 leads to diminished surface flaws in $CsPbBr_3$, which consequently lowers the non-radiative recombination rate of carriers, leading to a notable enhancement in luminescence duration.	[98]
$CsPbBr_3$/ Cs_4PbBr_6	conventional melting-quenching and heat-treatment technique	remained 80% of the original one	25 lmW^{-1}	58%	Through refining the raw materials and adjusting the melting parameters, it was possible to achieve a PLQY exceeding 58% while enhancing thermal stability, moisture resistance, light stability, and water resistance.	[99]
$CsPbBr_3$ PQD-SiO_2 and $CsPbBr_{1\cdot2}I_{1.8}$ PQD-SiO_2	solution route		35.4 lmW^{-1}	-	highly enhanced thermal stability and water stability	[100]

emitters, free MAPbBr3 NCs with a 20% quantum yield (QY) employed, and only low brightness and insufficient device performance reported. Zeng et al. [120] improved the brightness of perovskite NC-based LEDs through using bright CsPbBr3 NCs (PLQY greater than 85%) as the emitters, which reaches 946 cd m−2 at a voltage of 8.8 V. Due to the instability of iodine-based NC materials, it is more difficult to produce effective iodine-based perovskite NC LEDs than bromine-based perovskite NC LEDs. Initial research on CsPbI3 NC LEDs was focused on their performance [117].

Using a cross-linking method based on trimethylaluminum (Al2(CH3)6) vapor, the CsPbI3 nanocrystal film was enhanced in capturing electron-hole pairs, leading to the development of red LEDs with a peak EQE of 5.7% [119]. Zhang et al. [121] Demonstrated that a simple treatment of CsPbI3 nanocrystals with polyethylenimine effectively reduced surface defects, leading to a significant enhancement in electroluminescence efficiency to 7.25%. Following this, the researchers started to consider the device's stability. By entirely epitaxially growing PbS semiconductor on the CsPbI3 NCs surface, Zhang et al. [122] Created a technique to enhance both the stability and optical characteristics of CsPbI3 nanocrystals while preserving their semiconductor properties intact. By introducing PbS capping, the CsPbI3 nanocrystal film transitioned from n-type to almost ambipolar behavior, enabling the fabrication of LEDs with p-i-n structures. These LEDs exhibited enhanced performance and longevity, along with an EQE of 11.8% [122]. Using SrCl2 as a co-precursor while synthesizing CsPbI3 NCs, Lu et al. developed a method to enhance both the EL and photoluminescence (PL) efficiencies in order to make LEDs more efficient and stable. As a consequence, NCs with Cl surface passivation and simultaneous Sr doping, were produced, and devices employing these emitters demonstrated improved stability and EQE of 13.5% [123].

Utilizing Zn-alloyed CsPbI3 NCs to act as emitters allowed for a subsequent increase in the device's EQE to 15.1%. CsPb0.64Zn0.33I3 is the element found in the most effective and stable NCs. In addition to NC LEDs based on pure Bromine or Iodine component NCs, mixed halogen perovskite NC devices have also been investigated. Mixed halogen NCs offer more choices on the emitting color, which is promising in high-purity color display [124].

Even while luminance and efficiency for green-emitting LEDs have significantly increased in just over a year, considerable work still has to be done to better understand the processes that cause NCs to degrade, create efficient red and blue LEDs, stabilize their color, and optimize the device architecture. While chemists all over the world are continuously manufacturing novel perovskite NCs, all these constitute significant obstacles [125].

The presence of lead in the crystal continues to fuel the exploration for new structures and compositions of perovskite NCs.The expectation is that the knowledge acquired in producing LEDs with solely inorganic or hybrid lead perovskite nanocrystals can eventually be applied to their environmentally friendly versions. The toxicity of lead-based perovskite remains a major hindrance to their practical use.Also , All-inorganic perovskites made of cesium and lead halides have shown great potential as semiconductor materials in various fields such as lighting, display technology, light detection, and lasers. However, the durability of lead halide perovskites poses a significant issue because of their delicate ionic crystal framework and the presence of surface-coordinated states that are highly dynamic. To address this issue, the CsPbBr3@Cs4PbBr6 composite nanocrystals have been optimized to exhibit excellent light emission performance and enhanced stability against atmospheric conditions, moisture, and heating. Leimeng Xu et al [84]. were able to achieve a remarkable 135% enhancement in the NTSC color gamut by employing anion exchange. The resulting composite NCs, characterized by their exceptional emissive properties and enhanced stability, hold significant promise for various optoelectronic applications in the future.

6. Conclusions

Inorganic perovskites possess alluring optical and electronic attributes, making them highly promising for optoelectronic uses and sparking considerable research attention. However, the unfavorable structural and chemical stability of these materials is the greatest hindrance to dependable device performance. Review of the research conducted on inorganic perovskite composites in an effort to improve their stability and efficacy as LED. The optical properties and efficacy of composites comprised of inorganic perovskite were discussed. According to the findings of recent studies, composites of inorganic perovskite can increase chemical stability. Additionally, the quantum efficiency and optical properties of LED based inorganic perovskites have been enhanced through doping and formation of composites. The proportion of composites' constituent materials, in the optical properties of LEDs are crucial, so it is recommended to use new, cost-effective, and scalable materials to obtain the best LED performance.

REFERENCES

[1] C.M. Bourget, An introduction to light-emitting diodes, HortScience 43(7) (2008) 1944-1946.

[2] S.A. Veldhuis, P.P. Boix, N. Yantara, M. Li, T.C. Sum, N. Mathews, S.G. Mhaisalkar, Perovskite materials for light-emitting diodes and lasers, Advanced materials 28(32) (2016) 6804-6834.

[3] N. Yeh, T.J. Ding, P. Yeh, Light-emitting diodes′ light qualities and their corresponding scientific applications, Renewable and Sustainable Energy Reviews 51 (2015) 55-61.

[4] R. Pode, B. Diouf, R. Pode, B. Diouf, Light Emitting Diodes, Solar Lighting (2011) 61-95.

[5] K. Ji, M. Anaya, A. Abfalterer, S.D. Stranks, Halide Perovskite Light-Emitting Diode Technologies, Advanced Optical Materials 9(18) (2021) 2002128.

[6] V. Adinolfi, W. Peng, G. Walters, O.M. Bakr, E.H. Sargent, The electrical and optical properties of organometal halide perovskites relevant to optoelectronic performance, Advanced Materials 30(1) (2018) 1700764.

[7] L. Zhang, X. Yang, Q. Jiang, P. Wang, Z. Yin, X. Zhang, H. Tan, Y. Yang, M. Wei, B.R. Sutherland, Ultra-bright and highly efficient inorganic based perovskite light-emitting diodes, Nature communications 8(1) (2017) 15640.

[8] L. Protesescu, S. Yakunin, M.I. Bodnarchuk, F. Krieg, R. Caputo, C.H. Hendon, R.X. Yang, A. Walsh, M.V. Kovalenko, Nanocrystals of cesium lead halide perovskites (CsPbX3, X= Cl, Br, and I): novel optoelectronic materials showing bright emission with wide color gamut, Nano letters 15(6) (2015) 3692-3696.

[9] J. Liang, J. Liu, Z. Jin, All-inorganic halide perovskites for optoelectronics: progress and prospects, Solar Rrl 1(10) (2017) 1700086.

[10] X. Zhang, B. Xu, J. Zhang, Y. Gao, Y. Zheng, K. Wang, X.W. Sun, All-inorganic perovskite nanocrystals for high-efficiency light emitting diodes: dual-phase CsPbBr3-CsPb2Br5 composites, Advanced Functional Materials 26(25) (2016) 4595-4600.

[11] T.A. Wani, J. Shamsi, X. Bai, N. Arora, M.I. Dar, Advances in All-Inorganic Perovskite Nanocrystal-Based White Light Emitting Devices, ACS omega (2023).

[12] Y. Wang, H. Sun, All-inorganic metal halide perovskite nanostructures: from photophysics to light-emitting applications, Small Methods 2(1) (2018) 1700252.

[13] K. Wei, B. Liang, C. Sun, Y. Jiang, M. Yuan, Metal Halide Perovskites for Red-Emission Light-Emitting Diodes, Small Structures 3(10) (2022) 2200063.

[14] J. Yu, G. Liu, C. Chen, Y. Li, M. Xu, T. Wang, G. Zhao, L. Zhang, Perovskite CsPbBr 3 crystals: growth and applications, Journal of Materials Chemistry C 8(19) (2020) 6326-6341.

[15] Y. Rakita, N. Kedem, S. Gupta, A. Sadhanala, V. Kalchenko, M.L. Böhm, M. Kulbak, R.H. Friend, D. Cahen, G. Hodes, Low-temperature solution-grown CsPbBr3 single crystals and their characterization, Crystal Growth & Design 16(10) (2016) 5717-5725.

[16] Y.-M. Chen, Y. Zhou, Q. Zhao, J.-Y. Zhang, J.-P. Ma, T.-T. Xuan, S.-Q. Guo, Z.-J. Yong, J. Wang, Y. Kuroiwa, Cs4PbBr6/CsPbBr3 perovskite composites with near-unity luminescence quantum yield: large-scale synthesis, luminescence and formation mechanism, and white light-emitting diode application, ACS applied materials & interfaces 10(18) (2018) 15905-15912.

[17] Y. Zhang, L. Chouhan, E. Fron, L. Leoncino, K. Elkhouly, H. Bhatia, W. Qiu, M.B. Roeffaers, J. Hofkens, E. Debroye, Operationally Stable and Efficient CsPbI3–x Br x Perovskite Nanocrystal Light-Emitting Diodes Enabled by Ammonium Ligand Surface Treatment, Acs Photonics 10(8) (2023) 2774-2783.

[18] X. Lian, X. Wang, Y. Ling, E. Lochner, L. Tan, Y. Zhou, B. Ma, K. Hanson, H. Gao, Light emitting diodes based on inorganic composite halide perovskites, Advanced Functional Materials 29(5) (2019) 1807345.

[19] J. Xu, W. Huang, P. Li, D.R. Onken, C. Dun, Y. Guo, K.B. Ucer, C. Lu, H. Wang, S.M. Geyer, Imbedded nanocrystals of CsPbBr3 in Cs4PbBr6: kinetics, enhanced oscillator strength, and application in light-emitting diodes, Advanced Materials 29(43) (2017) 1703703.

[20] G. Jin, D. Zhang, P. Pang, Z. Ye, T. Liu, G. Xing, J. Chen, D. Ma, Boosting the performance of CsPbBr 3-based perovskite light-emitting diodes via constructing nanocomposite emissive layers, Journal of Materials Chemistry C 9(3) (2021) 916-924.

[21] G. Pacchioni, Highly efficient perovskite LEDs, Nature Reviews Materials 6(2) (2021) 108-108.

[22] I.E. Titkov, S.Y. Karpov, A. Yadav, V.L. Zerova, M. Zulonas, B. Galler, M. Strassburg, I. Pietzonka, H.-J. Lugauer, E.U. Rafailov, Temperature-dependent internal quantum efficiency of blue high-brightness light-emitting diodes, IEEE Journal of Quantum Electronics 50(11) (2014) 911-920.

[23] T. Morgenstern, C. Lampe, T. Naujoks, M. Jurow, Y. Liu, A.S. Urban, W. Brütting, Elucidating the performance limits of perovskite nanocrystal light emitting diodes, Journal of Luminescence 220 (2020) 116939.

[24] H. Zhao, G. Liu, J. Zhang, R.A. Arif, N. Tansu, Analysis of internal quantum efficiency and current injection efficiency in III-nitride light-emitting diodes, Journal of Display Technology 9(4) (2013) 212-225.

[25] W. Brütting, J. Frischeisen, T.D. Schmidt, B.J. Scholz, C. Mayr, Device efficiency of organic light-emitting diodes: Progress by improved light outcoupling, physica status solidi (a) 210(1) (2013) 44-65.

[26] S.F. Wu, S.H. Li, Y.K. Wang, C.C. Huang, Q. Sun, J.J. Liang, L.S. Liao, M.K. Fung, White Organic LED with a Luminous Efficacy Exceeding 100 lm W− 1 without Light Out-Coupling Enhancement Techniques, Advanced Functional Materials 27(31) (2017) 1701314.

[27] L. Zhang, L. Mei, K. Wang, Y. Lv, S. Zhang, Y. Lian, X. Liu, Z. Ma, G. Xiao, Q. Liu, Advances in the application of perovskite materials, Nano-Micro Letters 15(1) (2023) 177.

[28] C.C. Stoumpos, M.G. Kanatzidis, The renaissance of halide perovskites and their evolution as emerging semiconductors, Accounts of chemical research 48(10) (2015) 2791-2802.

[29] Y. Zheng, S. Yang, Stabilization techniques of lead halide perovskite for photovoltaic applications, Solar RRL 6(1) (2022) 2100710.

[30] M. Lu, Y. Zhang, S. Wang, J. Guo, W.W. Yu, A.L. Rogach, Metal halide perovskite light-emitting devices: promising technology for next-generation displays, Advanced Functional Materials 29(30) (2019) 1902008.

[31] C.-H. Lu, G.V. Biesold-McGee, Y. Liu, Z. Kang, Z. Lin, Doping and ion substitution in colloidal metal halide perovskite nanocrystals, Chemical Society Reviews 49(14) (2020) 4953-5007.

[32] F. Zhang, H. Lu, J. Tong, J.J. Berry, M.C. Beard, K. Zhu, Advances in two-dimensional organic–inorganic hybrid perovskites, Energy & Environmental Science 13(4) (2020) 1154-1186.

[33] Z.-K. Tan, R.S. Moghaddam, M.L. Lai, P. Docampo, R. Higler, F. Deschler, M. Price, A. Sadhanala, L.M. Pazos, D. Credgington, Bright light-emitting diodes based on organometal halide perovskite, Nature nanotechnology 9(9) (2014) 687-692.

[34] J. Jin, M.C. Folgueras, M. Gao, S. Yu, S. Louisia, Y. Zhang, L.N. Quan, C. Chen, R. Zhang, F. Seeler, A New Perspective and Design Principle for Halide Perovskites: Ionic Octahedron Network (ION), Nano letters 21(12) (2021) 5415-5421.

[35] X. Li, X. Shen, Q. Lv, P. Guo, L. Xiao, Metal Halide Perovskites: Promising Materials for Light-Emitting Diodes, Coatings 14(1) (2024)83.

[36] B. Chaudhary, Y.K. Kshetri, H.-S. Kim, S.W. Lee, T.-H. Kim, Current status on synthesis, properties and applications of CsPbX3 (X = Cl, Br, I) perovskite quantum dots/nanocrystals, Nanotechnology 32(50) (2021) 502007.

[37] S.A. Kulkarni, S.G. Mhaisalkar, N. Mathews, P.P. Boix, Perovskite nanoparticles: synthesis, properties, and novel applications in photovoltaics and LEDs, Small Methods 3(1) (2019) 1800231.

[38] J.-N. Yang, T. Chen, J. Ge, J.-J. Wang, Y.-C. Yin, Y.-F. Lan, X.-C. Ru, Z.-Y. Ma, Q. Zhang, H.-B. Yao, High color purity and efficient green light-emitting diode using perovskite nanocrystals with the size overly exceeding bohr exciton diameter, Journal of the American Chemical Society 143(47) (2021) 19928-19937.

[39] X. Fan, X. Yang, X. Kong, T. Zhang, S. Wang, Y. Lin, Z. Chen, Recent progresses on perovskite quantum dots patterning techniques for color conversion layer in micro-LED displays, Next Nanotechnology 5 (2024) 100045.

[40] L. Protesescu, S. Yakunin, M.I. Bodnarchuk, F. Krieg, R. Caputo, C.H. Hendon, R.X. Yang, A. Walsh, M.V. Kovalenko, Nanocrystals of Cesium Lead Halide Perovskites (CsPbX3, X = Cl, Br, and I): Novel Optoelectronic Materials Showing Bright Emission with Wide Color Gamut, Nano Letters 15(6) (2015) 3692-3696.

[41] L.N. Quan, F.P. García de Arquer, R.P. Sabatini, E.H. Sargent, Perovskites for light emission, Advanced Materials 30(45) (2018) 1801996.

[42] X. Du, G. Wu, J. Cheng, H. Dang, K. Ma, Y.-W. Zhang, P.-F. Tan, S. Chen, High-quality CsPbBr 3 perovskite nanocrystals for quantum dot light-emitting diodes, RSC advances 7(17) (2017) 10391-10396.

[43] H.C. Wang, Z. Bao, H.Y. Tsai, A.C. Tang, R.S. Liu, Perovskite quantum dots and their application in light-emitting diodes, Small 14(1) (2018) 1702433.

[44] N.K. Kumawat, A. Swarnkar, A. Nag, D. Kabra, Ligand engineering to improve the luminance efficiency of CsPbBr3 nanocrystal based light-emitting diodes, The Journal of Physical Chemistry C 122(25) (2018) 13767-13773.

[45] L. Wang, B. Liu, X. Zhao, H.V. Demir, H. Gu, H. Sun, Solvent-Assisted Surface Engineering for High-Performance All-Inorganic Perovskite Nanocrystal Light-Emitting Diodes, ACS Applied Materials & Interfaces 10(23) (2018) 19828-19835.

[46] B. Han, B. Cai, Q. Shan, J. Song, J. Li, F. Zhang, J. Chen, T. Fang, Q. Ji,X. Xu, Stable, efficient red perovskite light-emitting diodes by (α, δ)-CsPbI3 phase engineering, Advanced Functional Materials 28(47) (2018)1804285.

[47] D. Yang, P. Li, Y. Zou, M. Cao, H. Hu, Q. Zhong, J. Hu, B. Sun, S. Duhm,Y. Xu, Interfacial synthesis of monodisperse CsPbBr3 nanorods with tunable aspect ratio and clean surface for efficient light-emitting diode applications, Chemistry of Materials 31(5) (2019) 1575-1583.

[48] W.H. Jeong, S. Lee, H. Song, X. Shen, H. Choi, Y. Choi, J. Yang, J.W. Yoon, Z. Yu, J. Kim, Synergistic Surface Modification for High-Efficiency Perovskite Nanocrystal Light-Emitting Diodes: Divalent Metal Ion Doping and Halide-Based Ligand Passivation, Advanced Science 11(4) (2024) 2305383.

[49] P. Lu, T. Li, M. Lu, C. Ruan, S. Sun, Z. Wu, Y. Zhong, F. Zhang, Y. Gao,Y. Huang, Enrichment of anchoring sites by introducing supramolecular halogen bonds for the efficient perovskite nanocrystal LEDs, Light: Science& Applications 12(1) (2023) 215.

[50] J. Song, J. Li, L. Xu, J. Li, F. Zhang, B. Han, Q. Shan, H. Zeng, Room-temperature triple-ligand surface engineering synergistically boosts ink stability, recombination dynamics, and charge injection toward EQE-11.6% perovskite QLEDs, Advanced Materials 30(30) (2018) 1800764.

[51] M. Lu, H. Wu, X. Zhang, H. Wang, Y. Hu, V.L. Colvin, Y. Zhang,W. W. Yu, Highly flexible CsPbI3 perovskite nanocrystal light-emitting diodes,Chem NanoMat 5(3) (2019) 313-317.

[52] J.H. Park, A.-y. Lee, J.C. Yu, Y.S. Nam, Y. Choi, J. Park, M.H. Song, Surface ligand engineering for efficient perovskite nanocrystal-based light-emitting diodes, ACS applied materials & interfaces 11(8) (2019) 8428-8435.

[53] M. Lu, J. Guo, P. Lu, L. Zhang, Y. Zhang, Q. Dai, Y. Hu, V.L. Colvin, W.W. Yu, Ammonium thiocyanate-passivated CsPbI3 perovskite nanocrystals

for efficient red light-emitting diodes, The Journal of Physical Chemistry C 123(37) (2019) 22787-22792.

[54] H. Chen, L. Fan, R. Zhang, W. Liu, Q. Zhang, R. Guo, S. Zhuang, L. Wang, Sodium ion modifying in situ fabricated CsPbBr3 nanoparticles for efficient perovskite light emitting diodes, Advanced Optical Materials 7(21) (2019) 1900747.

[55] Y. Huang, W. Luan, M. Liu, L. Turyanska, DDAB-assisted synthesis of iodine-rich CsPbI 3 perovskite nanocrystals with improved stability in multiple environments, Journal of Materials Chemistry C 8(7) (2020) 2381-2387.

[56] Y. Zhu, J. Zhao, G. Yang, X. Xu, G. Pan, Ammonium acetate passivated CsPbI 3 perovskite nanocrystals for efficient red light-emitting diodes, Nanoscale 12(14) (2020) 7712-7719.

[57] Y.-F. Lan, J.-S. Yao, J.-N. Yang, Y.-H. Song, X.-C. Ru, Q. Zhang, L.-Z. Feng, T. Chen, K.-H. Song, H.-B. Yao, spectrally stable and efficient pure red CsPbI3 quantum dot light-emitting diodes enabled by sequential ligand post-treatment strategy, Nano Letters 21(20) (2021) 8756-8763.

[58] M. Jiang, Z. Hu, L.K. Ono, Y. Qi, CsPbBr x I 3-x thin films with multiple ammonium ligands for low turn-on pure-red perovskite light-emitting diodes, Nano Research 14 (2021) 191-197.

[59] W. Feng, K. Lin, W. Li, X. Xiao, J. Lu, C. Yan, X. Liu, L. Xie, C. Tian, D. Wu, Efficient all-inorganic perovskite light-emitting diodes enabled by manipulating the crystal orientation, Journal of Materials Chemistry A 9(17) (2021) 11064-11072.

[60] M. Liu, Q. Wan, H. Wang, F. Carulli, X. Sun, W. Zheng, L. Kong, Q. Zhang, C. Zhang, Q. Zhang, Suppression of temperature quenching in perovskite nanocrystals for efficient and thermally stable light-emitting diodes, Nature Photonics 15(5) (2021) 379-385.

[61] C. Tang, X. Shen, S. Yu, Y. Zhong, Z. Wang, J. Hu, M. Lu, Z. Wu, Y. Zhang, W.Y. William, Post-treatment of CsPbI3 nanocrystals by p-iodo-D-Phenylalanine for efficient perovskite LEDs, Materials Today Physics 21 (2021) 100555.

[62] Y.K. Wang, F. Yuan, Y. Dong, J.Y. Li, A. Johnston, B. Chen, M.I. Saidaminov, C. Zhou, X. Zheng, Y. Hou, All-inorganic quantum-dot LEDs based on a phase-stabilized α-CsPbI3 perovskite, Angewandte chemie international edition 60(29) (2021) 16164-16170.

[63] Q. Qiao, Z. Shen, N. Jiang, P. Song, D. Song, B. Qiao, S. Zhao, Z. Xu, Synergistic effect of multidentate ligands on CsPbI3 perovskite nanocrystals surface for high efficiency deep red light-emitting diode, Organic Electronics 107 (2022) 106550.

[64] J.K. Park, S.Y. Kim, J.H. Kim, J.H. Heo, S.H. Im, Spray-coated nanocrystalline CsPbBr3 perovskite thin-films for large area and efficient rigid and flexible light emitting diodes, Journal of Alloys and Compounds 918 (2022) 165560.

[65] M.T. Hoang, A.S. Pannu, Y. Yang, S. Madani, P. Shaw, P. Sonar, T. Tesfamichael, H. Wang, Surface treatment of inorganic CsPbI3 nanocrystals with guanidinium iodide for efficient perovskite light-emitting diodes with high brightness, Nano-Micro Letters 14(1) (2022) 69.

[66] J. Zhang, W. Shen, S. Chen, Z. Zhang, B. Cai, Y. Qiu, Y. Liu, J. Jiang, Y. He, M. Nan, Multidentate ligand-passivated CsPbI3 perovskite nanocrystals for stable and efficient red-light-emitting diodes, The Journal of Physical Chemistry Letters 14(29) (2023) 6639-6646.

[67] F. Zhao, H.W. Duan, S.N. Li, J.L. Pan, W.S. Shen, S.M. Li, Q. Zhang, Y.K. Wang, L.S. Liao, Iodotrimethylsilane as a Reactive Ligand for Surface Etching and Passivation of Perovskite Nanocrystals toward Efficient Pure-red to Deep-red LEDs, Angewandte Chemie International Edition 62(46) (2023)e202311089.

[68] B. Du, Y. Xia, Q. Wei, G. Xing, Y. Chen, W. Huang, All-Inorganic Perovskite Nanocrystals-Based Light Emitting Diodes and Solar Cells,ChemNanoMat 5(3) (2019) 266-277.

[69] Y. Yu, Y. Zhou, Y. Zhang, Y. Zhang, X. Liu, X. Liang, J. Liu, S. Chen, W. Xiang, Novel CsPbX3@mica composites with excellent optical properties for high efficiency and wide color gamut white light-emitting diode, Journal of Luminescence 236 (2021) 118129.

[70] J. Zhu, Z. Xie, X. Sun, S. Zhang, G. Pan, Y. Zhu, B. Dong, X. Bai, H. hang, H. Song, Highly efficient and stable inorganic perovskite quantum dots by embedding into a polymer matrix, ChemNanoMat 5(3) (2019) 346-351.

[71] B.G. Krishna, D.S. Ghosh, S. Tiwari, Tuning optical properties of CsPbBr 3 perovskite nanocrystals through silver doping, Journal of Materials Science: Materials in Electronics (2021) 1-13.

[72] X. Li, Y. Wu, S. Zhang, B. Cai, Y. Gu, J. Song, H. Zeng, CsPbX3 quantum dots for lighting and displays: room-temperature synthesis, photoluminescence superiorities, underlying origins and white light-emitting diodes, Advanced Functional Materials 26(15) (2016) 2435-2445.

[73] Q. Mo, T. Shi, W. Cai, S. Zhao, D. Yan, J. Du, Z. Zang, Room temperature synthesis of stable silica-coated CsPbBr3 quantum dots for amplified spontaneous emission, Photon. Res. 8(10) (2020) 1605-1612.

[74] L. Zhu, S. Yuan, J. Cheng, L. Chen, C. Liu, H. Tong, H. Zeng, Q. Cheng, Room temperature in-situ synthesis of inorganic lead halide perovskite nanocrystals sol using ultraviolet polymerized acrylic monomers as solvent and their composites with high stability, Applied Sciences 10(9) (2020)3325.

[75] X. Xu, H. He, Z. Fang, H. Lou, C. Lin, L. Chen, Z. Ye, Ultrasonication-assisted ambient-air synthesis of monodispersed blue-emitting CsPbBr3 quantum dots for white light emission, ACS Applied Nano Materials 2(11) (2019) 6874-6879.

[76] Y. Qin, S. Hu, Q. Shen, H. Hu, X. Luo, J. Liu, J. Yuan, D. Xu, Ultrasonic synthesis of perovskite-type BaCeO 3/Fe 2 O 3 composites with enhanced photocatalytic degradation of Rhodamine B, Functional Materials Letters 16(02) (2023) 2351005.

[77] Z. Bao, Y.-C. Chang, H.-C. Wang, Y.-C. Lee, T.-L. Tsai, R.-S. Liu, Synthesis of ultra-stable perovskite composite quantum dots for light-emitting diodes, Green Chemistry 23(22) (2021) 8871-8877.

[78] Y. Ling, L. Tan, X. Wang, Y. Zhou, Y. Xin, B. Ma, K. Hanson, H. Gao, Composite perovskites of cesium lead bromide for optimized photoluminescence, The Journal of Physical Chemistry Letters 8(14) (2017) 3266-3271.

[79] M. Ban, Y. Zou, J.P. Rivett, Y. Yang, T.H. Thomas, Y. Tan, T. Song, X. Gao, D. Credgington, F. Deschler, Solution-processed perovskite light emitting diodes with efficiency exceeding 15% through additive-controlled nanostructure tailoring, Nature communications 9(1) (2018) 3892.

[80] Y.P. Wang, H.C. Li, Y.C. Huang, C.S. Tan, Synthesis and Applications of Halide Perovskite Nanocrystals in Optoelectronics, Inorganics 11(1) (2023) 39.

[81] P. Wang, B. Wang, Y. Liu, L. Li, H. Zhao, Y. Chen, J. Li, S. Liu, K. Zhao, Ultrastable perovskite–zeolite composite enabled by encapsulation and in situ passivation, Angewandte Chemie 132(51) (2020) 23300-23306.

[82] S. Gonzalez-Carrero, R.E. Galian, J. Pérez-Prieto, Maximizing the emissive properties of CH 3 NH 3 PbBr 3 perovskite nanoparticles, Journal of Materials Chemistry A 3(17) (2015) 9187-9193.

[83] V. Amendola, I. Fortunati, C. Marega, A.L. Abdelhady, M.I. Saidaminov, O.M. Bakr, High-Purity Hybrid Organolead Halide Perovskite Nanoparticles Obtained by Pulsed-Laser Irradiation in Liquid, ChemPhysChem 18(9) (2017)1047-1054.

[84] L. Xu, J. Li, T. Fang, Y. Zhao, S. Yuan, Y. Dong, J. Song, Synthesis of stable and phase-adjustable CsPbBr 3@ Cs 4 PbBr 6 nanocrystals via novel anion–cation reactions, Nanoscale Advances 1(3) (2019) 980-988.

[85] S.-J. Woo, J.S. Kim, T.-W. Lee, Characterization of stability and challenges to improve lifetime in perovskite LEDs, Nature Photonics 15(9) (2021) 630-634.

[86] G. Hu, W. Qin, M. Liu, X. Ren, X. Wu, L. Yang, S. Yin, Scalable room-temperature synthesis of plum-pudding-like Cs4PbBr6/CsPbBr3 microcrystals exhibiting excellent photoluminescence, Journal of Materials Chemistry C 7(16) (2019) 4733-4739.

[87] Q.A. Akkerman, S. Park, E. Radicchi, F. Nunzi, E. Mosconi, F. De Angelis, R. Brescia, P. Rastogi, M. Prato, L. Manna, Nearly monodisperse insulator Cs4PbX6 (X= Cl, Br, I) nanocrystals, their mixed halide compositions, and their transformation into CsPbX3 nanocrystals, Nano letters 17(3) (2017) 1924-1930.

[88] L.N. Quan, R. Quintero-Bermudez, O. Voznyy, G. Walters, A. Jain, J.Z. an, X. Zheng, Z. Yang, E.H. Sargent, Highly emissive green perovskite nanocrystals in a solid state crystalline matrix, Advanced Materials 29(21) (2017) 1605945.

[89] Y. Wei, H. Xiao, Z. Xie, S. Liang, S. Liang, X. Cai, S. Huang, A.A. Al Kheraif, H.S. Jang, Z. Cheng, Highly luminescent lead halide perovskite quantum dots in hierarchical CaF2 matrices with enhanced stability as phosphors for white light-emitting diodes, Advanced Optical Materials 6(11) 2018) 1701343.

[90] F.Zhang,Z.-F.Shi,Z.-Z.Ma,Y.Li,S.Li,D.Wu,T.-T.Xu,X.-J.Li,C.-X. Shan, G.-T. Du, Silica coating enhances the stability of inorganicperovskite nanocrystals for efficient and stable down-conversion in whitelight-emitting devices, Nanoscale 10(43) (2018) 20131-20139.

[91] S. Lou, T. Xuan, Q. Liang, J. Huang, L. Cao, C.Yu, M. Cao, C. Xia, J.Wang, D. Zhang, Controllable and facile synthesis of CsPbBr3-Cs4PbBr6perovskite composites in pure polar solvent, Journal of colloid and interfacescience 537 (2019)384-388.

[92] E. Mei,X.Liu,Y.Chen,Y.Yu,Z.Chen,K.Yang,X.Liang,W.Xiang,Modified α-Al2O3 wafer: Enhance the stability of perovskite quantum dotswith wide colourgamut for white light-emitting diodes, Applied SurfaceScience569 (2021)150964.

[93] M. He,C.Wang,J.Li,J.Wu,S.Zhang, H.-C.Kuo,L. Shao,S. Zhao,J.Zhang, F. Kang, G. Wei, CsPbBr3–Cs4PbBr6composite nanocrystals forhighlyefficient pure green light emission, Nanoscale 11(47) (2019) 22899-22906.

[94] S. Chen, J. Lin, S. Zheng, Y. Zheng, D. Chen, Efficient and StablePerovskite White Light-Emitting Diodes for Backlit Display, AdvancedFunctionalMaterials(2023)2213442.

[95] C.Y. Zhong, L. Li, Q. Chen, K.Z. Jiang, F.t. Li, Z.Q. Liu, Y. Chen, Enhanced Exciton-to-Mn2+ Energy Transfer in 3D/0D Cesium–Lead–Chloride CompositePerovskites, Advanced Optical Materials 11(4) (2023) 2202321.

[96] C. Fan, H. Liu, J. Zhou, X. Dai, H. He, Z. Ye, Ultrastable and highlyefficient CsPbBr3 composites achieved by dual-matrix encapsulation fordisplaydevices,InfoMat(2023)e12417.

[97] T. Xuan, S. Guo, W. Bai, T. Zhou, L. Wang, R.-J. Xie, Ultrastable andhighlyefficientgreen-emittingperovskite quantumdotcomposites forMini-LED displays or backlights, Nano Energy 95 (2022) 107003.

[98] M.Fan,J.Huang,L.Turyanska,Z.Bian,L.Wang,C.Xu,N.Liu,H.Li,X. Zhang ,C. Zhang, Efficient All-Perovskite White Light-Emitting DiodesMade of In Situ GrownPerovskite-Mesoporous Silica Nanocomposites,Advanced Functional Materials (2023) 2215032.

[99] B.Yang,F.Zheng,S.Mei,Z.Chen,Y.Xie,H.Dai,X.Wei,W.Zhang,F.Xie, J. Ju,Y. Chu,J.Zou, R.Guo,Component regulation and crystallizationmechanism of CsPbBr3/Cs4PbBr6 perovskite composite quantum dots-embedded borosilicate glass for light emitting application, Applied SurfaceScience512 (2020)145655.

[100] D.H. Park, J.S. Han, W. Kim, H.S. Jang, Facile synthesis of thermally stable CsPbBr3 perovskite quantum dot-inorganic SiO2 composites and the irapplication to white light-emitting diodes with wide color gamut, Dyes and Pigments 149 (2018) 246-252.

[101] Y.-H. Kim, S. Kim, A. Kakekhani, J. Park, J. Park, Y.-H. Lee, H. Xu, S. Nagane, R.B. Wexler, D.-H. Kim, Comprehensive defect suppression in perovskite nanocrystals for high-efficiency light-emitting diodes,Nature Photonics 15(2) (2021)148-155.

[102] X.-K. Liu, W. Xu, S. Bai, Y. Jin, J. Wang, R.H. Friend, F. Gao, Metal halide perovskites for light-emitting diodes, Nature Materials 20(1) (2021) 10-21.

[103] Y.-H. Kim, S. Kim, A. Kakekhani, J. Park, J. Park, Y.-H. Lee, H. Xu, S. Nagane, R.B. Wexler, D.-H. Kim, S.H. Jo, L. Martínez-Sarti, P. Tan, A. Sadhanala, G.-S. Park, Y.-W. Kim, B. Hu, H.J. Bolink, S. Yoo, R.H. Friend, A.M. Rappe, T.-W. Lee, Comprehensive defect suppression in perovskite nanocrystals for high-efficiency light-emitting diodes, Nature Photonics 15(2) (2021) 148-155.

[104] M.A. Triana, E.-L. Hsiang, C. Zhang, Y. Dong, S.-T. Wu, Luminescent nanomaterials for energy-efficient display and healthcare, ACS Energy Letters 7(3) (2022) 1001-1020.

[105] G. Li, K. Chen, Y. Cui, Y. Zhang, Y. Tian, B. Tian, Y. Hao, Y. Wu, H. Zhang, Stability of perovskite light sources: status and challenges, Advanced Optical Materials 8(6) (2020) 1902012.

[106] L. Zhang, L. Mei, K. Wang, Y. Lv, S. Zhang, Y. Lian, X. Liu, Z. Ma, G. Xiao, Q. Liu, S. Zhai, S. Zhang, G. Liu, L. Yuan, B. Guo, Z. Chen, K. Wei, A. iu, S. Yue, G. Niu, X. Pan, J. Sun, Y. Hua, W.-Q. Wu, D. Di, B. Zhao, J. Tian, Z. Wang, Y. Yang, L. Chu, M. Yuan, H. Zeng, H.-L. Yip, K. Yan, W. Xu, L. hu, W. Zhang, G. Xing, F. Gao, L. Ding, Advances in the Application of Perovskite Materials, Nano-Micro Letters 15(1) (2023)177.

[107] J.S. Du, D. Shin, T.K. Stanev, C. Musumeci, Z. Xie, Z. Huang, M. Lai, L. Sun, W. Zhou, N.P. Stern, Halide perovskite nanocrystal arrays: Multiplexed synthesis and size-dependent emission, Science Advances 6 (39) (2020) eabc4959.

[107] J.S. Du, D. Shin, T.K. Stanev, C. Musumeci, Z. Xie, Z. Huang, M. Lai, L. Sun, W. Zhou, N.P. Stern, Halide perovskite nanocrystal arrays: Multiplexed synthesis and size-dependent emission, Science Advances 6(39) (2020) eabc4959.

[108] Z. Ma, Z. Shi, D. Yang, F. Zhang, S. Li, L. Wang, D. Wu, Y. Zhang, G. Na, L. Zhang, Electrically-driven violet light-emitting devices based on highly stable lead-free perovskite Cs3Sb2Br9 quantum dots, ACS Energy Letters 5(2) (2019) 385-394.

[109] L. Bai, S. Wang, Y. Zhang, K. Zhang, H. Li, K. Ou, L. Yi, Investigation on violet/blue all-inorganic light-emitting diodes based on CsPbCl3 films, Journal of Luminescence 226 (2020) 117422.

[110] Q.A. Akkerman, V. D'Innocenzo, S. Accornero, A. Scarpellini, A. Petrozza, M. Prato, L. Manna, Tuning the optical properties of cesium lead halide perovskite nanocrystals by anion exchange reactions, Journal of the American Chemical Society 137(32) (2015) 10276-10281.

[111] J. Harwell, J. Burch, A. Fikouras, M.C. Gather, A. Di Falco, I.D. Samuel, Patterning multicolor hybrid perovskite films via top-down lithography, ACS nano 13(4) (2019) 3823-3829.

[112] C. Zou, C. Chang, D. Sun, K.F. Böhringer, L.Y. Lin, Photolithographic patterning of perovskite thin films for multicolor display applications, Nano Letters 20(5) (2020) 3710-3717.

[113] P.M. Pattison, M. Hansen, J.Y. Tsao, LED lighting efficacy: Status and directions, Comptes Rendus Physique 19(3) (2018) 134-145.

[114] A. Liu, C. Bi, R. Guo, M. Zhang, X. Qu, J. Tian, Electroluminescence Principle and Performance Improvement of Metal Halide Perovskite Light-Emitting Diodes, Advanced Optical Materials 9(18) (2021) 2002167.

[115] M. Vasilopoulou, A. Fakharuddin, F.P. García de Arquer, D.G. Georgiadou, H. Kim, A.R.b. Mohd Yusoff, F. Gao, M.K. Nazeeruddin, H.J. Bolink, E.H. Sargent, Advances in solution-processed near-infrared light-emitting diodes, Nature Photonics 15(9) (2021) 656-669.

[116] H. Cho, S.-H. Jeong, M.-H. Park, Y.-H. Kim, C. Wolf, C.-L. Lee, J.H. Heo, A. Sadhanala, N. Myoung, S. Yoo, Overcoming the electroluminescence efficiency limitations of perovskite light-emitting diodes, Science 350(6265) (2015) 1222-1225.

[117] J. Song, J. Li, X. Li, L. Xu, Y. Dong, H. Zeng, Quantum dot light-emitting diodes based on inorganic perovskite cesium lead halides (CsPbX3), Advanced materials 27(44) (2015) 7162-7167.

[118] J. Li, L. Xu, T. Wang, J. Song, J. Chen, J. Xue, Y. Dong, B. Cai, Q. Shan, B. Han, 50-Fold EQE improvement up to 6.27% of solution-processed all-inorganic perovskite CsPbBr3 QLEDs via surface ligand density control,Advanced Materials 29(5) (2017) 1603885.

[119] G. Li, F.W.R. Rivarola, N.J. Davis, S. Bai, T.C. Jellicoe, F. de la Peña, S. Hou, C. Ducati, F. Gao, R.H. Friend, Highly efficient perovskite nanocrystal light-emitting diodes enabled by a universal crosslinking method, Advanced materials 28(18) (2016) 3528-3534.

[120] Q. Zeng, X. Zhang, C. Liu, T. Feng, Z. Chen, W. Zhang, W. Zheng, H. hang, B. Yang, Inorganic CsPbI2Br perovskite solar cells: the progress and perspective, Solar Rrl 3(1) (2019) 1800239.

[121] X. Zhang, C. Sun, Y. Zhang, H. Wu, C. Ji, Y. Chuai, P. Wang, S. Wen, C. Zhang, W.W. Yu, Bright perovskite nanocrystal films for efficient light-emitting devices, The journal of physical chemistry letters 7(22) (2016) 4602 -4610.

[122] X. Zhang, M. Lu, Y. Zhang, H. Wu, X. Shen, W. Zhang, W. Zheng, V.L. Colvin, W.W. Yu, PbS capped CsPbI3 nanocrystals for efficient and stable light-emitting devices using p–i–n structures, ACS Central Science 4(10) (2018) 1352-1359.

[123] M. Lu, X. Zhang, Y. Zhang, J. Guo, X. Shen, W.W. Yu, A.L. Rogach, Simultaneous strontium doping and chlorine surface passivation improve luminescence intensity and stability of CsPbI3 nanocrystals enabling efficient light-emitting devices, Advanced Materials 30(50) (2018) 1804691.

[124] X. Shen, Y. Zhang, S.V. Kershaw, T. Li, C. Wang, X. Zhang, W. Wang,D. Li, Y. Wang, M. Lu, Zn-alloyed CsPbI3 nanocrystals for highly efficient perovskite light-emitting devices, Nano letters 19(3) (2019) 1552-1559.

[125] A. Perumal, S. Shendre, M. Li, Y.K.E. Tay, V.K. Sharma, S. Chen, Z.ei, Q. Liu, Y. Gao, P.J.S. Buenconsejo, High brightness formamidinium lead bromide perovskite nanocrystal light emitting devices, Scientific Reports 6(1) (2016) 36733.