Recent advancements in halide perovskite nanomaterials and their optoelectronic applications

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Abstract
Lead halide perovskite nanomaterials are among the forefront of developing materials for energy harvesting and light-emitting applications. Their unique defect tolerance, high photoluminescent quantum yields, and vast synthetic tunability make them attractive for many optoelectronic applications. In this review article, the broad synthetic toolbox of these materials is discussed, including how synthetic conditions can tune the optical properties and dimensionality of the resulting perovskite nanomaterial. Additionally, we discuss the brief history, current state, and bright future of these materials, in tune with their optoelectronic applications, namely in light-emitting diodes, lasing, photovoltaics, photon interconversion applications, and in photodetectors.

KEYWORDS
halide perovskites, light-emitting diodes, nanomaterials, photodetectors, photon interconversion, photovoltaics

1 | INTRODUCTION

The advent and development of semiconductor quantum dots (QDs) have led to an explosion of research and innovation across many different fields. Applications include lighting, displays, lasing, and photovoltaics (PV). These take advantage of the unique properties of QDs, many stemming from the effects of quantum confinement. The discovery of the quantum size effect in colloidal QDs in the 1980s and 1990s showed that the emission wavelength of these materials is tunable by their size, as shown in Figure 1(A). As the degree of quantum confinement increases, so too does the bandgap of the material. While early research focused on colloidal CdE (where E = S, Se, Te) QDs, this has quickly blossomed into research focused on all aspects of QDs, including composition, tuning of the organic ligands surrounding the QDs, and also dimensionality. Tuning of the synthetic conditions can lead to nanomaterials with a lessened degree of quantum confinement, which results in distinct properties. A collection of nanomaterials with differing dimensionality are shown in Figure 1(B), including zero-dimensional (0D) QDs, 1D nanorods (NRs), and nanowires (NWs), along with 2D nanoplatelets (NPLs) and nanosheets (NSs). As shown, not only the dimensionality can differ but also the aspect ratio of the material, leading to the different properties of each material. For example, perovskite NPLs feature stronger amounts of quantum confinement as compared to their QD counterparts, leading to blue-shifted emission. Additionally, some unique properties stem from anisotropicity, shown in materials such as 1D NRs or 2D NPLs, where these materials can be oriented into macrostructures and the anisotropic nature of these materials can yield polarized emission, depending on the orientation of the material. While early QD research...
mainly focused on metal chalcogenides, for example, CdSe and PbS, metal halide perovskite (MHP) QDs have quickly shown their relevance, and in some cases, have supplanted metal chalcogenide materials in various applications, for example, PV devices, where they have surpassed metal chalcogenides in efficiency. Perovskite nanomaterials have many other applications, which will be discussed in detail in Section 3. MHP materials are called perovskites due to their crystal structure resembling CaTiO₃, the mineral named for Lev Perovski, where a cationic species A sits between adjacent octahedra comprised of a cationic species B in the center and anionic species X on the edges, as shown in Figure 2(A). In MHPs, A is a monovalent metal cation such as Cs⁺, or an organic cation, where methylammonium (MA) or formamidinium (FA) is the most common. B is a divalent metal, commonly Pb²⁺ or Sn²⁺, and X is comprised of a halide, either Cl, Br, or I, resulting in a formula comprised of ABX₃.

MHP materials comprised of A-site organic cations are commonly termed as hybrid organic–inorganic perovskites, while perovskites with Cs⁺ as the A-site cation are commonly referred to as all-inorganic perovskite materials. MHP materials are not novel materials, as they were first discovered in the 1890s, but they were not intensely studied until the late 2000s, when they were first used as visible light sensitizers for PV cells. In the last decade, perovskite PV technologies have exploded in relevance, thanks in large part to the increase in efficiency from 3.8% to 25.5%. Additionally, these materials have been studied in other applications including but not limited to light-emitting diodes (LEDs), lasers, photodetectors, triplet–triplet annihilation-based upconversion (TTA-UC), catalysis, and memory.

The two fields previously mentioned: colloidal QDs and bulk perovskites were first fused in 2014, when Pérez-Prieto and coworkers synthesized colloidal MAPbBr₃ using a solution-based precipitation method and then subsequently increased the emission quantum yield from 20% to 83%. Soon after, all inorganic CsPbX₃ QDs were synthesized via a hot-injection method.
developed by Kovalenko and coworkers. Although synthesized similarly to the widely studied metal chalcogenide materials, early research into perovskite QDs (PQDs) uncovered key differences in the materials. First, the electronic structure of MHP material differs from metal chalcogenides in that defects and trap states are found inside either the valence band (VB) or conduction band (CB), whereas defects can lead to red-shifted emission in metal chalcogenides due to the trap states falling in between the VB and CB, as depicted in Figure 2(B). This key difference leads to the “defect-tolerance” of PQDs, which results in inherently high photoluminescent quantum yields (PLQYs), defined as the percentage of photons emitted by a material per the photons absorbed by the same material. Additionally, CsPbX3 PQDs represent the first example of an inorganic semiconductor possessing a bright “triplet” state.

This initial research in colloidal PQDs blossomed into perovskite nanomaterials of varying dimensionalities, synthesized through subtle tuning of the synthetic conditions used to form PQDs. Early reports of 1D and 2D perovskite nanomaterials include 1D NWs made using a modified hot-injection synthesis. Additionally, 2D NPLs and NSs have been synthesized using varying methods. Like PQDs, these materials typically have superior optical properties but can also exhibit other unique properties due to their anisotropic nature. For example, 1D and 2D materials of varying composition have been shown to form complex ordered structures, which could be useful for many applications.

We note that layered low-dimensional perovskites, or “perovskite-related” materials also exist and have wide applications similar to the ones discussed here, yet we yield to the definition of a metal-halide perovskite as stated by Akkerman et al. and leave these materials beyond the scope of this work. While differences in optical properties can stem from dimensionality, several other factors can lend to the optical properties of these perovskite materials, including synthetic method, synthetic conditions including solvents and temperature, surface–ligand interactions, and many more. These choices act as a synthetic toolbox of sorts, meaning that these choices can lead to vastly different properties, which could be taken advantage of in different applications. Here, we will carefully examine the synthetic conditions, ligand interactions, and postsynthetic processing of perovskite nanomaterials of varying dimensions, including how these choices can mold the material for many various applications. These applications will then be discussed, highlighting achievements of these various nanomaterials, before an outlook on the hopefully "bright" future of this class of materials.

2 | SYNTHESIS OF PEROVSKITE NANOMATERIALS

Although Perez-Prieto and coworkers were the first to demonstrate the successful synthesis of PQDs in solution, the use of hot injection to synthesize all inorganic CsPbX3 quickly revolutionized the field of perovskite nanomaterials. To this day, two main synthesis methods exist to synthesize perovskite nanomaterials. These two methods, as detailed in Figure 3, are the hot-injection method and methods based on reprecipitation (especially at room temperature) including both emulsion-based syntheses and ligand-assisted reprecipitation (LARP). Figure 3(A) details a schematic of the hot-injection synthesis where a complex of the A-site cation with an oleate is injected into a lead salt/ligand solution at an increased temperature. Figure 3(B) details a ligand-assisted reprecipitation approach, where a precursor salt solution is injected into an antisolvent, typically at room temperature.
method is shown generally in Figure 3(B). Typically, the precursor salts are dissolved into solution, and then formation is induced by addition into an antisolvent, as will be discussed later.

2.1 Perovskite nanomaterial general synthetic methods

Although ubiquitous for other QD materials for decades, the hot-injection method was first demonstrated for PQDs by Protesceu et al.,\textsuperscript{42} where a solution containing cesium oleate is injected into another solution containing lead bromide at a temperature of 150°C. Additionally, OA and oleylamine ligands are present in the solution, which aid in passivating the PQD surface. Figure 4(A,B) shows the result of their synthetic approach, where vastly tunable and narrow emission peaks can be observed by tuning the halide composition through the synthetic process.\textsuperscript{42} Soon after, the hot-injection method was tuned to synthesize perovskite NPLs by decreasing the reaction temperature.\textsuperscript{47} Bekenstein et al.\textsuperscript{47} showed that by decreasing the temperature from 150°C to 130°C, green-emitting cubic PQDs give way to cyan-emitting NPLs. Additionally, decreasing the temperature further to 90°C results in thin blue-emitting NPLs. The hot-injection method can also be utilized to grow colloidal perovskite NWs. Yang and coworkers showed that simply increasing the reaction time and temperature could allow PQDs to grow into NWs.\textsuperscript{45} The reaction temperature and time then can be tuned to yield different dimension perovskite materials.

The first synthesis of MAPbBr\textsubscript{3} PQDs shown by Schmidt et al.\textsuperscript{40} utilized a solvent precipitation method, where methylammonium bromide and PbBr\textsubscript{2} were added to a warm (80°C) solution containing long-chain ammonium bromide and OA ligands in octadecene (ODE). Upon addition of acetone, the PQDs were readily precipitated from solution. Figure 4(C) shows the transmission electron microscopy image of one of these as-synthesized PQDs. Subsequent studies of the MAPbBr\textsubscript{3} PQDs showed that the elimination of OA could boost the PLQY from 20% to above 80%.\textsuperscript{41} The resulting bright emission upon UV excitation by a simple laser pointer is shown in Figure 4(D).

Reports of materials with differing dimensionalities soon followed. Teunis et al.\textsuperscript{52} reported MAPbBr\textsubscript{3} NWs grown using a similar synthesis, as they proposed that the NWs grew from the as-synthesized PQDs. Subsequent studies of the MAPbBr\textsubscript{3} PQDs showed that the elimination of OA could boost the PLQY from 20% to above 80%.\textsuperscript{41} The resulting bright emission upon UV excitation by a simple laser pointer is shown in Figure 4(D).

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LARP is another similar, yet highly convenient method for the synthesis of perovskite nanomaterials. The LARP method consists of the addition of the perovskite precursors as salts of the targeted halide into one precursor solution, utilizing a solvent that is “good” for the precursor salts, for example, dimethylformamide (DMF) or dimethyl sulfoxide (DMSO), until the mixture forms an equilibrium. Forcing the solution to deviate from equilibrium, typically through the addition of a “bad” solvent for the precursor salts, for example, toluene then yields the desired nanomaterial in solution. LARP was first used for the synthesis of MAPbX3 PQDs by Zheng et al., where PQDs exhibited wide tunability of size and, therefore, emission wavelength, and also reported PLQYs of ~80%. It was also used to synthesize a host of NPLs with varying compositions, as shown by Weidman et al. Perovskite NPLs of one and two monolayers were synthesized using LARP by tuning the ratio of precursors. Additionally, the A, B, and X sites were varied to monitor NPLs of varying composition. MA, FA, and Cs were used as A-site cations, Pb and Sn were used as B-site cations, and the halide was tuned from Cl to Br to I in many of these compositions. While these NPL materials were shown to be vastly tunable, they suffer from stability issues. 1D perovskite NWs were also synthesized using LARP, where relatively stable micron length NWs with a 2.6 nm width were synthesized by Kostopoulou et al. Interestingly, these NWs aggregated over time, causing the increase of the NW width, but they also remained relatively stable, as the excess of halides passivated the NW surfaces.

Semiconductor NWs have been extensively studied for photonic applications, including lasers and photodetectors. The development of vapor-phase synthetic methods such as chemical vapor deposition (CVD) and epitaxial methods allow for fine control over the properties of NWs. Recently, these methods have been applied to perovskite NWs. MAPbX3 NWs were first made using CVD by Xing et al. Specifically, PbX2 NWs were grown onto a substrate, which were then converted to perovskite NWs by MAX through a gas–solid reaction. The MAPbX3 NWs exhibited low lasing thresholds and as good as 2.2 nm width were synthesized by Xing et al. Specifically, PbX2 NWs were grown via van der Waals epitaxy for use as lasing materials by Zhang et al. Additionally, nanoplates were grown onto indium tin oxide (ITO) prepatterned electrodes using vapor-phase deposition, resulting in electro-luminescent devices. Perovskite microplatelets have also been grown via solution-phase methods, namely through chemical vapor deposition (CVD), resulting in materials useful for multiple optoelectronic applications. Wu and coworkers have recently developed one-step CVD methods for perovskite NPLs, allowing for the elucidation of the exciton binding energy for increasingly thin NPLs. Additionally, these perovskite NPL materials can be grown onto graphene to fabricate a van der Waals heterostructure, which could prove useful for fabricating novel optoelectronic devices.

Hot injection, LARP, and emulsion-based syntheses are typically the most common for modern perovskite nanomaterials. These synthetic methods can be thought of as “bottom-up” synthetic methods, where the conditions are chosen to produce more complex materials from atoms or molecules. Conversely, “top-down” methods result in smaller materials from larger materials as a result of mechanical or chemical fragmentation. While the majority of perovskite nanomaterials are made through bottom-up methods, top-down methods could prove useful as a synthetic option, as some top-down methods, for example, ball milling, are relatively green and inexpensive options for fabricating these perovskite nanomaterials. Ball milling has been previously demonstrated to synthesize PQDs, while mechanical exfoliation has been used to make perovskite NPLs. These mechanochemical methods could prove to be useful for the synthesis of perovskite nanomaterials, as they do not require solvents, resulting in a greener synthetic method. However, ball milling can limit the PLQY of the material, as initial synthetic methods had PLQYs of 40%, due to the formation of surface trap states. The PLQY of PQDs can further be increased to 80% when ligand treatments are used, but the necessary redissolution into solvent postsynthesis then goes against the original motivation without substantial improvements. Although these mechanochemical methods have already shown promise in bulk phase perovskite synthesis, further work is needed to improve this method for the synthesis of perovskite nanomaterials.

2.2 Perovskite nanomaterial ligands: Effects and advances

Nanomaterials of varying composition and dimension are highly impacted by the ligand choice, as structure, colloidal stability, and inherent performance are shaped by surface interactions with the ligand. For perovskite
nanomaterials, the surface ligands are vital for mitigating surface defects and improving the PLQY of the material. Additionally, by tuning the size and type of ligand used in synthesis, the dimensionality of the material can be tuned.

Historically, the PQD surface was passivated through the addition of two ligand species, long-chain carboxylic acids and amines, typically OA and oleylamine, respectively.42 The specific nature of the ligand-binding dynamics was elucidated by De Roo et al.,77 where it was determined through nuclear magnetic resonance spectroscopy (NMR) that oleylamine binds to the surface of the PQD via the formation of oleylammonium bromide. Upon additional oleylamine addition, OA can bind to the surface via the formation of oleylammonium oleate.77 This can be elucidated through nuclear Overhauser effect spectroscopy (NOESY), as shown in Figure 5(A) (left). Both the OA and oleylamine peaks show a negative response, meaning they interact with the surface. This only occurs after oleylamine addition, meaning that the oleylamine is forming oleylammonium oleate (upon deprotonation of OA) as well as oleylammonium bromide, as shown in the right side of Figure 5(A).77 This study also showed the highly dynamic nature of these ligands.77 This dynamic nature, along with the propensity to rapidly desorb from the surface, especially upon addition of polar solvent, can cause rapid decreases in the PL performance of the material.77 Fortunately, there are many ligand-based strategies geared at improving the stability and, therefore, the PL performance of these materials.

By using ligands that are able to tightly bind to the surface, the likelihood of ligand desorption decreases. Zwitterionic ligands, as demonstrated by Kovalenko and coworkers,78 are able to tightly bind to the PQD surface and are capable of coordinating to both surface cations and anions. The schematic of this approach is shown in Figure 5(B). Consequently, they observed PLQYs in excess of 90% employing this strategy.78 Phosphonic acid ligands are also capable of binding tightly to PQD surfaces, typically coordinated to Pb2+ ions, which can greatly increase the PLQY of the PQD material.80,81 Phosphonic acid ligands will irreversibly exchange with native OA ligands upon addition, resulting in a higher steady-state PL intensity upon ligand exchange.82

Imran et al.83,84 found that quaternary ammonium bromide (QAB) ligands, which are added via ligand exchange can increase the QY to near unity. However, this is not due to the tight binding of the ligand to the PQD surface, as discussed previously, but due to differences in solvent–ligand interactions compared to the

**Figure 5**

(A) Nuclear Overhauser effect spectroscopy (NOESY) spectrum of CsPbBr3 perovskite QDs after postsynthetic addition of oleylamine (left) and schematic detailing the dynamic binding nature of the ligands after oleylamine addition (right). Adapted from reference 77. Copyright 2016 American Chemical Society. (B) Schematic detailing a tight-binding ligand approach using zwitterionic ligands that contain both a cationic and an anionic site. Adapted from reference 78. Copyright 2018 American Chemical Society. (C) Schematic detailing the difference in reaction temperature and ligand size on the resulting size and shape of the nanomaterial. Reproduced from reference 79. Copyright 2016 American Chemical Society
native ligand, allowing for the QAB ligands to better bind to the surface.\textsuperscript{83} Another amine ligand, didodecyl dimethyl ammonium bromide, or DDAB, has been shown to improve the passivation of PQD surfaces after introduction by Pan et al.\textsuperscript{85} DDAB is exceedingly useful for devices such as LEDs which require shorter chain ligands, as it decreases the size of the amine ligand while improving the performance of the device.\textsuperscript{85–87}

This wealth of surface-ligand knowledge is important for PQDs, but also materials of differing dimensions, such as perovskite NPLs. Perovskite NPLs have a tendency to coalesce, resulting in red-shifted emission and the loss of quantum confinement and PLQY due to poor stability and ligand desorption.\textsuperscript{58,88,89} While the addition of an excess of ligands can increase the stability of the NPLs at least temporarily,\textsuperscript{58} ligand exchange to a more tightly binding ligand could be a promising approach toward improving PL performance of these materials. This is demonstrated by Shamsi et al., where hexyl phosphonate ligands are used to cap CsPbBr\textsubscript{3} NPLs, resulting in a PLQY of 40% with continued stability under ambient conditions.\textsuperscript{90}

While the surrounding ligand shell is important for the PL performance of the perovskite material, it can also dictate the dimension of the material. Early tuning of the size and type of ligand used resulted in different size and dimensionality of the resulting perovskite nanomaterial. In hot-injection syntheses, the findings from an investigation from Pan et al.\textsuperscript{79} can be summarized in Figure 5(C). They found that in general, low reaction temperatures favored NPL growth, while high temperatures favored QD growth, as previously observed by Bekenstein et al.\textsuperscript{47} However, they further observed that the length of each ligand could tune the size and shape of the material. Even at higher temperatures (>140°C), the use of a shorter chain amine resulted in NPLs, while short amines resulted in thinner NPLs at low temperatures.\textsuperscript{79} By tuning the size of the acid ligand, the size of the PQD could be tuned, as high temperatures and shorter chain ligands resulted in larger PQDs.\textsuperscript{79}

The addition of even more ligands, for example, dodecylamine, octylamine, and octanoic acid, in addition to the common OA and oleylamine, was shown to yield thin perovskite NSs.\textsuperscript{91,92} Omitting the acid ligand was also shown to result in perovskite NWs,\textsuperscript{93} while Imran et al.\textsuperscript{94} demonstrated that size control of the acid ligand could yield control of the diameter of the NW.

Control of the size and shape of the material can also be controlled by the size and type of ligand used in LARP synthetic methods as well. Cho et al.\textsuperscript{85} found that by tuning the amine ligand chain length alongside OA, the thickness of the perovskite NPL could be tuned. Additionally, Sichert et al.\textsuperscript{54} were able to make perovskite NPLs without carboxylic acid ligands in 2015.

### 2.3 | Perovskite surface treatments

As previously discussed, the use of ligands that bind tightly to the surface of the perovskite nanomaterial, either used as the native ligand or through ligand exchange, can improve the passivation of surface defects, resulting in higher PLQYs of the material. As more tightly binding ligands are typically geared toward binding to Pb\textsuperscript{2+} ions, many surface treatment strategies are aimed at passivating undercoordinated Pb sites, which can act as surface traps.\textsuperscript{96} The overabundance of anions such as Br\textsuperscript{−} in the form of PbBr\textsubscript{2} and thiocyanate was shown to greatly improve the PLQY of CsPbBr\textsubscript{3}, as the Pb-induced surface traps were passivated.\textsuperscript{77,96,97} Other sources of halide ions have been used to improve the optical performance of perovskite nanomaterials. ZnBr\textsubscript{2} has also been shown to increase the PLQY and stability of PQDs through surface passivation.\textsuperscript{98} A recent report by Zeng and coworkers showed that an in situ HBr treatment can increase the PLQY to near unity in perovskite NPLs.\textsuperscript{99}

The addition of cationic species in surface treatments is also known to improve the surface passivation and thus increase the performance of perovskite nanomaterials. In CsPbx\textsubscript{3}, PQDs, both K\textsuperscript{+} and Ag\textsuperscript{+} ions have been shown to passivate Cs-deficient areas, increasing the PLQY of these PQD materials.\textsuperscript{100–102} Additionally, Cu\textsuperscript{+} ions passivate the surface of CsPbCl\textsubscript{3} PQDs but also can tune the shape of the material from QDs to NWs.\textsuperscript{103}

### 2.4 | Perovskite nanomaterial doping and ion exchange

One of the most fascinating properties of PQDs is their ability to exchange the halide anions while maintaining their size and shape, which was first demonstrated by Kovalenko and coworkers.\textsuperscript{104} The exchange of the halide ion allows for facile control of the emission wavelength without changing the size of the PQD, where the emission can be tuned from ~400 to 700 nm, as shown in Figure 6(A). The size of the PQDs does not change, but the emission (shown in each inset) can be tuned by either adding Cl\textsuperscript{−} to CsPbBr\textsubscript{3} PQDs (top row) or by adding I\textsuperscript{−} (bottom row).\textsuperscript{104} The emission properties of perovskite nanomaterials can also be tuned by modulating the A and B-site cations. Mixed organic/inorganic A-site cations in both mixed bromide/iodide and iodide only perovskite compositions were examined in PQDs, NSs, and NWs.\textsuperscript{108,109} The stability of these compounds increased with contributions from both A-site species.\textsuperscript{108,109} Mixed inorganic A-site cations have also been studied, as both Amgar et al. and Wu et al. looked at the incorporation of Rb\textsuperscript{+} as an A-site cation in Cs\textsubscript{x}Rb\textsubscript{1-x}PbX\textsubscript{3}. 
The presence of Rb\textsuperscript+ shifted the bandgap to higher values, yielding blue-shifted emission.\cite{110,111} The B-site cation can also be tuned, where divalent cations such as Mn\textsuperscript{2+} can be doped into the perovskite, resulting in a modification of the emission wavelength. Mn\textsuperscript{2+} doping in PQDs was first reported by Parobek et al. and Klimov and coworkers, both in 2016.\cite{105,106} Figure 6 (B) shows the synthetic approach, where a modified hot-injection synthesis resulted in the formation of the Mn-doped PQDs. Mn\textsuperscript{2+} doping resulted in a red-shifted emission as compared to the undoped PQDs, as demonstrated by the photograph in Figure 6 (C), both made using a modified hot-injection reaction. The orange emission also had a much longer lifetime and higher PLQY.\cite{105,106} Furthermore, the stability is increased in Mn-doped perovskite nanocrystals, in both the phase and chemical stability.\cite{112} In an additional study, van der Stam et al.\cite{107} found that the B-site cation could be further tuned through a cation exchange method, where Pb\textsuperscript{2+} was exchanged for other divalent cations in PQDs, including Sn\textsuperscript{2+}, Cd\textsuperscript{2+}, and Zn\textsuperscript{2+}. Photographs of the emission of these cation-exchanged PQDs can be found in Figure 6 (D), showing the distinct shift in emission wavelength upon exchange of the B-site cation. The lattice contraction upon cation exchange was reflected in a blue-shift in the optical spectra due to the incorporation of smaller cations into the lattice.\cite{107} This method has also been recently expanded to include Ni\textsuperscript{2+}, which helped to increase the stability and PLQY of the PQDs.\cite{113} Lanthanides have also been used as dopants in perovskite nanomaterials, namely in PQDs, which could prove useful for a number of applications, including solid-state lighting and PVs.\cite{114,115} While doping has been widely explored in PQDs, it remains relatively unexplored in other shapes/dimensions of materials. Mn\textsuperscript{2+} doping has been realized in perovskite NPLs and NRs, where the bright orange d-d Mn\textsuperscript{2+} transition is observed, similarly to PQDs.\cite{119,120} Additionally, Fe\textsuperscript{3+} has been successfully doped into CsPbX\textsubscript{3} NWs, affecting both the morphology and optical properties of the material.\cite{121}

2.5 | Postsynthetic ordering/processing

For many applications, for example, PVs, the perovskite nanomaterials must be able to be integrated into
a solid-state device. Long-chain organic ligands, for example, OA and oleylamine, can hinder efficient packing into a thin film of PQDs or other materials. With typical QD materials, polar solvents are used to purify the QDs from reactants, reaction solvent, and to precipitate the colloidal QDs.\textsuperscript{122,123} However, polar solvents typically cause degradation and/or agglomeration of the PQDs.\textsuperscript{21} Additionally, ordering the PQDs into a film that allows for electronic coupling between the PQDs is important for many applications. For CsPbI\textsubscript{3} PQDs, a two-step solid-state ligand exchange process was able to both purify the PQDs while forming films with electronically coupled PQDs, resulting in highly efficient PV devices and LEDs.\textsuperscript{123–125}

In anisotropic perovskite materials, such as NWs, NRs, or NPLs, a film composed of ordered materials with the same orientation could allow for the orientation of the transition dipoles, allowing for the control of the polarization of the emission and long-range exciton diffusion through the material.\textsuperscript{18} While this has been realized in other semiconductor NPLs, for example, CdSe,\textsuperscript{18,126,127} rapid ligand desorption in the NPLs causes the NPLs to coalesce into each other forming stacks of nanobelts, and then finally large nanotiles.\textsuperscript{89} Finer control of the NPL self-assembly and ligand desorption could prove useful toward making perovskite NPL devices taking advantage of the anisotropic nature of the material.

The ordering of perovskite NWs is also an important endeavor due to the importance of the material in lasing, detecting, and other applications.\textsuperscript{62} Regardless of application, the performance of the NW material can deteriorate if the material is not highly crystalline or if the NW surfaces are rough or misaligned. To improve the quality of NW arrays, Deng et al.\textsuperscript{128} demonstrated a fluid-guided antisolvent vapor-assisted crystallization method using a photoresist to guide the growth of the NWs synthesized in solution. Photodetectors made using this method resulted in record responsivity for the material.\textsuperscript{128} The precise control of these NW arrays can be obtained through self-assembly methods,\textsuperscript{129,130} control of the solution-processing,\textsuperscript{131} or through other vapor-phase methods.\textsuperscript{62,132} Additionally, Lin et al.\textsuperscript{133} have demonstrated an inkjet printing strategy, which has allowed for NW arrays with increased stabilities, allowing for easily fabricated films capable of lasing across multiple wavelengths. This strategy has also been used to order perovskite NWs into an array which emit highly polarized light, which could prove useful for displays and many other optoelectronic applications.\textsuperscript{134}

Although perovskite NWs are sought for many applications, other applications may require objects such as NRs with lower aspect ratios as compared to NWs. Perovskite NRs are synthetically difficult to make, as their growth into high aspect ratio NWs is unable to be halted.\textsuperscript{135} However, using a halide ion exchange process via PbX\textsubscript{2}, Tong et al.\textsuperscript{136} were able to chemically cut the NWs to NRs while simultaneously increasing the PLQY of the material.

## 3 | APPLICATIONS

As mentioned, perovskite nanomaterials can be tuned in size, composition, and dimension. This broad tunability along with their superior optical properties makes them viable for many optoelectronic applications. Although perovskites are emerging materials, they have already revolutionized many fields. For example in PVs, where they currently hold the record for highest power conversion efficiency (PCE) for a QD-based solar cell,\textsuperscript{137} even though conventional colloidal QDs have been around for decades. This is just one example of the potential that MHP nanomaterials hold, and the progress and potential of these materials will be discussed further across many applications.

### 3.1 | Light-emitting diodes

One of the most commonly noted applications of PQDs and perovskite nanomaterials is in LEDs and other lighting sources for displays. The use of PQDs for LEDs has been the subject of many reviews\textsuperscript{138–141} and could draw inspiration from the commercialization of other QD LED technologies. As discussed previously, the optical properties of perovskite nanomaterials are tunable both by size, anion,\textsuperscript{104} and cation exchange,\textsuperscript{107} allowing for tunability across the visible spectrum, making them suitable for RGB display schemes. Additionally, their high PLQYs and narrow emission linewidths make them promising LED candidates. Soon after the emergence of PQDs, they received attention as possible LED materials. Song et al.\textsuperscript{142} demonstrated three different LEDs of different colors, as demonstrated in Figure 7(A), but saw low external quantum efficiencies (~0.1%). In the time since, the external quantum efficiencies of LEDs based on perovskite nanomaterials have exceeded 20%.\textsuperscript{144,146,147} The metrics used to quantify the performance of these materials will first be discussed, followed by the progress and potential of these perovskite materials for use as LEDs.

One of the most important metrics used for evaluating the performance of an LED is the external quantum efficiency (EQE). The EQE is defined as the number of photons emitted from the LED divided by the number of electrons injected into the LED, both quantified per
Additionally, the electroluminescence (EL) spectra of the LED can yield many important metrics, including most simply, the $\lambda_{\text{max}}$, or the peak emission wavelength, the luminance ($L$), which measures the intensity of light per unit area, given in units of cdM$^{-2}$. Ideally, the LED will have a high EQE at the given wavelength range at as high a luminance as possible.

Soon after the initial report of PQD LEDs, sequential improvements occurred to improve device performance, specifically geared toward device engineering, ligand engineering, and surface passivation of the PQDs. Shortly after the initial report of PQD LEDs with an EQE $\sim$0.1%, the development of a novel crosslinking method, which allowed for the deposition of charge injection layers, namely trimethylaluminum (TMA) without dissolution of the PQDs, increased the EQE of the device to 5.7%, albeit with a modest luminance of 206 cdM$^{-2}$. The crosslink approach is shown in Figure 7(B), where PQDs without TMA are washed off of the substrate, resulting in a lower retention ratio and PLQY. Longer TMA treatment times, however, result in crosslinked PQDs with higher performance.

Fine control of the ligands on the PQDs also proved useful for increasing the EQE of the LED devices, as a new washing procedure aimed at removing excess ligands resulted in an increase of the EQE to 8.73%, showing the importance at the engineering of the PQD ligands. Song et al. reached a new EQE efficiency threshold of 11.6% in 2018 using previously mentioned DDAB ligands, as well as other short-chain ligands tetraoctylammonium bromide and octanoic acid, which resulted in an increase in the PLQY of the PQDs and improved charge transport properties. Additionally, nonradiative decay pathways were suppressed by A-site doping, which further improved the PLQY and efficiency of the material. The same group, comprised of Zeng and coworkers, further pushed the efficiency of PQD LED devices to 16.48% by utilizing a new hybrid organic–inorganic ligand strategy to further passivate the PQDs. Chiba et al. used an anion exchange method that both redshifts the emission wavelength and passivates the surface. Long chain alkyl ammonium (OAM-I) and ary ammonium (An-HI) are added to as synthesized CsPbBr$_3$ QDs. Reprinted with permission from reference 144. Copyright 2018 Nature Publishing Group. (D) Photographs (left) of the untreated and calcium tributylphosphine oxide-treated CsPbCl$_3$ QDs under ambient lighting (top) and ultraviolet excitation (bottom) and photoluminescent spectra of CsPbCl$_3$ QDs treated with increasing amounts of calcium tributylphosphine oxide treatment. Adapted from reference 145 with permission. Copyright 2020 Elsevier.
method to push red-emitting PQD LEDs above 20% for the first time, with an EQE of 21.3% while still maintaining high color purity. This approach, shown in Figure 7(C), added the iodide anion through long-chain alkyl ammonium and aryl ammonium ligand salts. Almost simultaneously, Lin et al.\textsuperscript{146} reported green PQD LEDs with an EQE > 20% by tuning the composition through the addition of MABr, which formed a quasi-core/shell structure, increasing the stability and efficiency of the device. Blue-emitting PQD LEDs have also been the primary focus of many research efforts, as the EQE of blue-emitting PQD LEDs is much lower due to lower PLQYs of PQDs on the blue edge of their emission. One big step toward large-scale improvement of blue PQD LEDs was achieved by Wang et al.,\textsuperscript{152} where an EQE of 11% was achieved for a sky-blue-emitting LED and an EQE of 4.8% was obtained for a blue-emitting LED through the use of phenylethylammonium chloride and yttrium (III) chloride additives in the bulk films.

However, blue LEDs based on perovskite nanomaterials are still lagging behind, as PQD blue LEDs have only reached efficiencies of 3.3%.\textsuperscript{145} Yao et al.\textsuperscript{145} accomplished this feat through the use of calcium and tributylphosphine oxide to passivate the surface of the PQDs. This approach is highlighted in Figure 7(D), where the addition of the calcium and tributylphosphine oxide decreases the turbidity of the solution, increases the PLQY, and red shifts the emission.

Perovskite nanomaterials beyond PQDs have also been examined in LED devices. MAPbX\textsubscript{3} NPLs were studied shortly after their inception for LED devices spanning from blue, sky-blue, and green wavelengths of their EL emission.\textsuperscript{153,154} Perovskite NPLs have also been examined as materials that could prove useful as blue-emitting LED materials, although their relatively low stability has made this tougher to realize.\textsuperscript{58} Recently, Zeng and coworkers developed an in situ passivation technique, which aimed at passivating sites of halide vacancies, resulting in a near-unity PLQY of their CsPbBr\textsubscript{3} NPLs and an EQE of a blue-emitting LED of 0.124%.\textsuperscript{99} Further improvements in NPL materials could result in highly efficient blue LEDs. Current progress and most efficient devices (based on their EQE) are summarized in Table 1. Effective surface passivation, ligand and device engineering, and control of the material dimensionality without loss in performance are all methods that could prove useful in improving each wavelength range of LEDs.

### 3.2 Lasers and optical gain media

The bright and tunable emission of perovskite nanomaterials is useful for another application: lasing.
FIGURE 8  Legend on next page.
and optical gain media. Lasers must contain three basic parts, a gain medium, a source of energy, or “pump,” and a source of optical feedback. The gain medium is where population inversion takes place upon excitation via the pumping process. The optical feedback, typically in form of a cavity, provides feedback to the confined photons inside the gain medium, resulting in coherent and amplified emission given that the pump power is high enough. A lasing material with a “high gain” is able to produce amplified emission at relatively low pumping power, which is desirable.

Shortly after the synthesis of the first all-inorganic PQDs, 163,164 amplified spontaneous emission (ASE) was discovered in CsPbX₃ materials across the visible range, under low pump thresholds of 5 μJ cm⁻² at the minimum. 27 The broad tunability of the ASE observed is detailed in Figure 8(A), where the ASE is observed above the lasing threshold. Two separate lasing modes were observed in the material. They observed whispering-gallery mode lasing using silica microspheres as high-finesse resonators, which they coated with CsPbX₃ nanocrystals, as well as observing random lasing in films of CsPbX₃ nanocrystals. 27 Subsequent work saw the demonstration of continuous wave (CW) lasing at room temperature in green, red, and blue PQD films. 156 All three colors are shown in Figure 8(B), including a photograph of the green-emitting LED device (inset, left). The films were comprised of MAPbX₃ QDs suspended in a polymer matrix and had lasing thresholds an order of magnitude lower than lasing materials utilizing CdSe gain media. 156 Beyond PQDs, perovskite NWs have also been studied as a viable gain media.

Semiconductor NW lasers have revolutionized the field of lasing, as they represent nanomaterials that contain a gain medium and an inherent cavity, 60,160,161 that for some materials can inherently lase. Combining these properties with the tunability and excellent optical properties of perovskite materials results in the work done in perovskite NW lasing materials. Perovskite NW laser materials were first demonstrated by Zhu et al., 157 where MAPbX₃ NWs were grown using a surface-initiated growth strategy, resulting in a lower lasing threshold (220 nJ cm⁻²) than any other NW lasers up to that point. Figure 8(C) shows the bright emission in the photograph in the inset, where the emission can be observed at the facets of the NW. Further improvements of perovskite NW lasers involved stability improvements through tuning of the composition by substituting FA for MA and ultimately by using all-inorganic perovskite NW lasers by using Cs⁺ as the A-site cation. 158 Figure 8(D) shows the photographs of a CsPbX₃ NW below (first three) and above the lasing threshold. CsPbX₃ lasing materials proved to be much more stable, culminating in CW lasing in CsPbX₃ NWs in 2018. 159 As shown in Figure 8(E), the CW NW lasers were made in different size NWs and yielded laser emission at fluences above the lasing threshold. Further improvements in stability and engineering of these perovskite NW materials could continue to push the capabilities of these materials to induce high optical gain at low lasing thresholds. Additionally, further advancements could come from a better understanding of exciton–photon interactions in perovskite nanomaterials. 163,164 For example, insight into these interactions has shown that exciton–polariton interactions are key in the NW lasing scheme. 165,166 Further insights could yield more efficient lasers at lower lasing thresholds.

### 3.3 Photovoltaics

The space of perovskite PVs has been largely dominated by bulk perovskites, largely due to their monumental rise in power conversion efficiency (PCE), increasing from 3.8% to 25.2% from 2009 to 2020. 24,25 However, MHP nanomaterials can also be incorporated into PV materials, as PV materials based on colloidal QDs has been a field of research for well over a decade. 7,167 PV devices...
are most commonly graded off of their PCE, a measure of the output electrical power per light in, or how efficiently they can generate electricity from light. The PCE is given by the following equation as:

\[
\text{PCE} = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{V_{\text{max}}}{P_{\text{in}}} = \frac{V_{\text{oc}}J_{\text{sc}}\text{FF}}{P_{\text{in}}}
\]

where the \( P_{\text{out}} \) is the output electrical power, \( P_{\text{in}} \) is the incoming light power, \( V_{\text{max}} \) and \( J_{\text{max}} \) are the voltage and current density at the maximum power, \( V_{\text{oc}} \) is the open-circuit voltage, \( J_{\text{sc}} \) is the short circuit current density, and \( \text{FF} \) is the fill factor.\(^7\) \( V_{\text{oc}} \) yields the maximum voltage that a solar cell can generate, where \( J_{\text{sc}} \) represents the maximum number of charge carriers per unit area that can be extracted from the

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**FIGURE 9** Perovskite QD PV. (A) Representative J-V curve, where parameters such as the short circuit current density (\( J_{\text{sc}} \)), open circuit voltage (\( V_{\text{oc}} \)), max power (\( P_{\text{max}} \)), and fill factor (\( \text{FF} \)) can be extracted from the curve. (B) Schematic of the film deposition and AX salt treatment processes for a CsPbI\(_3\) QD device. Reproduced from reference \(^{124}\). © The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC). (C) Cross-sectional TEM image of the Cs\(_{1-x}\)FA\(_x\)PbI\(_3\) QD device structure (left). J-V curve of the Cs\(_{0.5}\)FA\(_{0.5}\)PbI\(_3\) QD device. Reproduced from reference \(^{137}\). Copyright 2017 Nature Publishing Group.
PV device. These factors can be observed from a typical J-V curve, as shown in Figure 9(A). In Table 2, these values are tabulated for quantum confined perovskite PV devices, in order to summarize the progress of these materials.

PQD solar cells first exceeded 10% PCE in 2016, when Luther and coworkers were able to successfully incorporate phase-stable CsPbI$_3$ PQDs into a PV device, resulting in a PCE of 10.77%. Additionally, the $V_{oc}$ of the device was 1.23 V, which was among the highest of any type of perovskite material. The key to these impressive achievements was through the use of methyl acetate as an antisolvent, which allowed for the removal of excess ligand and precursors without causing agglomeration of the PQDs.

Further work by the same group improved the PCE to 13.43% through A-site cation salt treatments while maintaining a high $V_{oc}$ at 80% of the maximum value. The A-site cation salt treatment is shown in Figure 9(B), where the treatment of the CsPbI$_3$ layers allows for highly mobile QDs, allowing for facile charge transfer in the QD layer. Similar approaches were probed by Ling et al., who employed Cs salt treatments to increase the PCE of their devices above 14%. The highest PCE for PQD PVs was achieved in 2020 by Hao et al., where tuning of the A-site cation resulted in an increase of the PCE to 16.6%. The cross section and J-V curve of the champion device are shown in Figure 9(C). This represents a record across all QD PV technologies, showing that perovskite materials hold promise in PVs beyond their bulk phase. Further optimization and device engineering in the form of surface passivation, ligand engineering, and increases in QD coupling could push PQD PV technologies on par with bulk perovskites.

### 3.4 Photon interconversion

Photon interconversion is important for applications such as the aforementioned field of PVs. In the photon upconversion process (UC), two incident photons are converted into a higher energy photon, while down-conversion (DC) represents the splitting of photons into multiple charge carriers or excitons. Upconverting two or more photons into one that is above the bandgap of PV materials such as the state-of-the-art silicon or splitting one photon into multiple charge carriers could allow for the Shockley–Queisser limit to be surpassed. MHP nanomaterials have been used in both UC and DC processes, sensitizing the triplet state of an organic polyaromatic hydrocarbon in triplet-triplet annihilation (TTA), as well as sensitizing a molecule capable of singlet fission (SF), a DC process, through a Dexter singlet energy transfer mechanism.

The process of TTA-UC is shown in Figure 10(A), where a sensitizer can perform an energy transfer mechanism to an acceptor triplet state, which can then undergo TTA when two anti-correlated triplet states combine to occupy a higher energy singlet state. The apparent anti-Stokes shift emission of the UC system then will be given by the difference between the sensitizer absorbance and the energy of the photon emitted upon relaxation of the excited singlet state in the acceptor molecule, again noting that the energy of the emission is higher than that in the absorption process. This is in contrast to most fluorophores, which exhibit a Stokes shift in their emission, meaning that the photons absorbed are higher in energy than the resultant emission.

TTA-UC is characterized by two main quantities, the UC quantum yield ($\Phi_{UC}$) and the power threshold $I_{th}$. The $\Phi_{UC}$ is defined as the number of UC photons emitted per photon absorbed. As TTA-UC is a two photon to one photon process, the maximum $\Phi_{UC}$ is 50%. The $I_{th}$ results from the unique power-dependent nature of UC emission intensity. At low power regimes, there is a quadratic dependence of the emission intensity relative to the incident power, where at high power regimes, the dependence is linear. The point at which the two regimes meet gives the $I_{th}$, the power at which TTA-UC becomes efficient. In PVs, $I_{th}$ values below solar flux are critical for the eventual industrial relevance.

Metal chalcogenide QDs, including PbS and CdSe, were first used as triplet sensitizers motivated by the large exchange energy losses in metal–organic triplet sensitizers. Shortly after the advent of all-inorganic CsPbX$_3$ PQDs, they were introduced as triplet sensitizers for TTA-UC by Mase et al. In this work, green-to-blue
UC occurred using an amine-derivatized triplet mediator coupled to the triplet annihilator 9,10-diphenylanthracene, shown by the energy level diagram in Figure 10(B) (left) at an $I_{th}$ of 25 mW cm$^{-2}$ (right), much lower than the aforementioned metal chalcogenide systems, but with a relatively lower $\Phi_{UC}$ of 0.65%, as compared to CdSe which had $\Phi_{UC}$ of 6% at the time. Subsequent studies involving perovskite QD triplet sensitizers both aimed at optimization and at different spectral ranges. Kimizuka and coworkers and Wu and coworkers concurrently found that CsPbX$_3$ can efficiently sensitize 2,5-diphenyloxazole via mediation from a 1-napthoic acid transmitter ligand, where the $\Phi_{UC}$ was 2% for the former and > 5% for the latter. The UC emission from PPO is shown in Figure 10(C), but the $I_{th}$ for this system is much higher than the green-to-blue system at ~1.9 W cm$^{-2}$. Additionally, Wu and coworkers have shown that PQDs with a higher degree of quantum confinement more efficiently sensitize the triplet state of a functionalized ligand, which would result in a higher $\Phi_{UC}$ upon addition of a triplet annihilator. Many other PQD sensitized works have been reported, investigating the dynamics of the exciton/electron transfer from perovskite to organic molecule, along with further optimizations.

Although a number of works recently have both optimized and elucidated the energy transfer pathways of PQD sensitized TTA-UC, neither 1D nor 2D perovskites have been used as triplet sensitizers, although this has been demonstrated in CdSe NPLs, meaning that as long as the energy levels are aligned, 1D or 2D perovskite materials could serve as triplet sensitizers. This sentiment is further echoed by the work done by Lian and coworkers and Gélvez-Rueda et al., who were able to induce charge separation by adding organic molecules as either hole or electron acceptors.

PQDs have also been used to sensitize the reverse process of SF. Figure 10(D) shows the ligand exchange scheme of an as-synthesized CsPbBr$_3$ perovskite QD capped with oleic acid (OA) ligands, resulting in trisopropylsilylethynyl pentacene carboxylic acid (TIPS-Pc) capped QDs (left) and the overall sensitization scheme of the singlet fission (SF) process (right).
lead chalcogenides, as QD acceptors for SF must be able to absorb in the near and short wave infrared. While progress is being made on pushing the capabilities of infrared absorbing PQDs, increases in the stability and performance of perovskite nanomaterials into the infrared will be crucial for the implementation of this material as a potential acceptor in SF.

Both the TTA-UC and SF processes described here require fine control of the triplet state of the organic molecule undergoing these processes. The triplet sensitization mechanism utilizing perovskite nanomaterials can extend beyond these processes, however. Triplet sensitization can also be useful for driving chemical processes. Recently, QDs have been used as triplet sensitizers for use in photocatalytic reactions. PQDs could prove useful for this purpose as well, as they have already been shown to be efficient triplet sensitizers, as discussed previously.

3.5 | Photodetectors

The same properties that make perovskite nanomaterials attractive for LEDs and PV (e.g., optical tunability, broadband absorption, and high charge carrier mobility) make them useful materials for photodetectors. Some important figures of merit of photodetectors include the responsivity (R), the quantum efficiency, the signal-to-noise ratio (SNR), and the specific detectivity (D*). The responsivity is the ratio of photocurrent generated per unit input power given in amperes per watt. The quantum efficiency is similar to the EQE of an LED, just in reverse, as it is equal to the number of electrons able to be extracted per the number of incident photons. The SNR is the amount of signal current (equal to responsivity and the incident optical power) over the current produced by noise. Ideally, the SNR is as large as possible for highly sensitive photodetectors. D* describes the detector’s sensitivity regardless of the device area, allowing for comparison of different shapes and sizes of detectors. This is useful, as perovskite nanomaterials of all shapes, sizes, and dimensions have been investigated for use as photodetectors, including QDs, NWs, NPLs, and NSs.

Ramasamy et al. first used anion exchanged CsPbBr\textsubscript{3} PQDs as photodetecting materials shortly after the first CsPbBr\textsubscript{3} hot-injection synthesis. The device structure is shown in Figure 11(A). Additionally, CsPbI\textsubscript{3} photodetectors were found to be fairly sensitive, as the photocurrent ratio was 10\textsuperscript{3} times higher under illumination. Subsequent studies aimed at improving the performance of the material, including through the integration of graphene, which resulted in an R of 10\textsuperscript{9} A W\textsuperscript{-1}, and a D* of 10\textsuperscript{16} Jones. The device structure is shown in Figure 10(B), where the graphene acted as a transport layer, and the increase in performance was attributed to the charge carrier transport properties of graphene. PQDs were also coupled to an upconversion material, namely NaYF\textsubscript{4}:Yb, Er QDs, allowing for photodetection from the ultraviolet to the infrared with high photosensitivity.

NW arrays have also been used as photodetecting materials. Deng et al. showed that MAPbX\textsubscript{3} perovskite NWs assembled through a solution-phase method could yield R values of 1.32 A W\textsuperscript{-1} and a D* of 2.5 × 10\textsuperscript{12} Jones. As shown in Figure 11(C), the NW devices were grown in a three-step patterned growth method. Additionally, these perovskite NW devices (pictured in the inset of the right side of Figure 11(C)) can be made transparent, a feat not possible with bulk materials. Perovskite NWs were fabricated on top of polyethylene terephthalate, resulting in devices with D* in excess of 10\textsuperscript{12} Jones while being both transparent and flexible.

Subsequent works have studied the MAPbX\textsubscript{3} NW system and made improvements in the quality of the NW devices. Single crystalline NWs were made by Tang and coworkers, resulting in an unprecedented D* of 2 × 10\textsuperscript{13} Jones. One other strategy is to weld together NWs into a NW network, allowing for a facile, large-scale approach, as demonstrated by Zeng and coworkers, as they welded a NW network resulting in a D* of 4.16 × 10\textsuperscript{12} Jones. This strategy of building NW networks for photodetectors could be useful for scaled-up devices. Additionally, further investigation into different A-site cations, such as Cs, could improve the stability of these devices.

NPLs and NSs have also be utilized as photodetecting materials. CsPbX\textsubscript{3} NSs grown in solution were shown to have a high sensitivity (on-off ratio > 10\textsuperscript{3}) in flexible photodetectors, as shown by Song et al. A schematic of this device is shown in Figure 11(D). Additionally, the addition of carrier “fast-tracks” in the form of carbon nanotubes was shown to greatly improve the performance, as the responsivity was 31 A W\textsuperscript{-1} for this system, over 125 times larger than the previous best. CsPbBr\textsubscript{3} NPLs can also yield high responsivities, as Liu et al. found a high 34 A W\textsuperscript{-1} responsivity for this system.

4 | OUTLOOK

While conventional QD materials have found commercial use in QLED displays, PQDs or other MHP nanomaterials for that matter, have not yet found industrial relevance. The reasons for the slow crawl in these
materials toward industrialization are the result of a combination of factors. MHPs, in both the bulk and at the nanoscale, are sensitive to air and moisture and are quick to degrade into their toxic parts under these ambient conditions. However, degradation even occurs in an encapsulated device, and the required long-term stability has not been achieved. Further improvements in perovskite nanomaterial stability or device encapsulation could come through an increased understanding of both the composition of the material and also through engineering of encapsulation materials, specifically functional materials such as polymer matrices.

Additionally, the hot-injection approach toward synthesizing these materials is difficult to scale up, as large-scale syntheses can be difficult to heat homogenously, and the process can be exceedingly expensive at scale. Synthesis-to-synthesis variations of the obtained nanomaterials due to slight variations in the precursor concentration or temperature lead to difficulties in the reproducibility of the obtained materials. The research into core–shell structures of perovskite nanomaterials is still in its infancy, compared to conventional semiconductor nanomaterials, where heterostructures are commonplace, and used to improve the stability and performance of these materials.

For commercial applications, an additional concern must also be addressed. The issues relating to reproducibility and stability are likely to be able to be addressed by careful synthetic strategies and device fabrication methods. However, the issue of toxicity remains. There is a push in the field toward lead-free perovskite materials, yet the common tin-based alternatives have not yielded the desired results due to their inherent instability, and additional environmental concerns. Future improvements in finding novel lead-free perovskite compositions should combine both theoretical and experimental approaches, especially as screening through methods such as machine learning could yield further insight in this aim.

Since perovskite nanomaterials and their applications are still emerging, the future of these materials remains bright.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

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