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REVIEW ARTICLE

Focus on performance of perovskite light-emitting diodes

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Abstract Perovskite-based optoelectronic devices, especially perovskite light-emitting diodes (PeLEDs) and perovskite solar cells, have recently attracted considerable attention. The National Renewable Energy Laboratory (NREL) chart inspires us to develop a counterpart for PeLEDs. In this study, we collect the record performance of PeLEDs including several new entries to address their latest external quantum efficiency (EQE), highest luminance, and stability status. We hope that these performance tables and future updated versions will show the frontiers of PeLEDs, assist researchers in capturing the overview of this field, identify the remaining challenges, and predict the promising research directions.

Keywords metal halide perovskite, light-emitting diode (LED), performance table

1 Introduction

Metal halide perovskites, a class of promising semiconductor materials with superior photoelectric properties, have produced a significant progress in solar cells, light-emitting diodes (LEDs), photodetectors, and lasers [1]. Thus far, the most active research area is solar cells, which enjoy a continually improved efficiency and growing commercial activities. Their efficiency evolution is available on the National Renewable Energy Laboratory (NREL) chart, which records the best certified efficiencies of state-of-the-art solar cells from 1976 to the present day. This chart allows readers to conveniently track industry trends and cutting-edge research status, which accelerates the advancement of this field.

However, until now, there has been no record line, chart, or even a review for perovskite light-emitting diodes (PeLEDs). In 2018, Cao et al. [2] and Lin et al. [3] have simultaneously reported highly efficient near-infrared and green PeLEDs with an external quantum efficiency (EQE) greater than 20%. The EQEs of PeLEDs matched those of commercial organic LEDs (OLEDs) in approximately four years after their development [4], which suggests the unparalleled potential of PeLEDs in lighting and display applications. Soon after, a red PeLED with an EQE of 21.6% was developed [5], which marked 2018 as a milestone in the development of PeLEDs. In addition, efficient blue PeLEDs have been recently reported [6,7]. Encouraged by the unprecedentedly rapid progress [8], more researchers have focused on PeLEDs and produced many encouraging results.

In this paper, we present useful tables containing world-class PeLEDs, aiming to provide researchers working on PeLED technologies with a valuable information resource. In addition, some performance tables summarize the core parameters of PeLEDs with the best EQE, record luminance, and noteworthy operation lifetime. Moreover, PeLEDs, which are based on lead-free materials and new manufacturing processes, are separately collected to exploit additional benefits. These tables will be renewed with the further progress of this field to provide additional support for researchers. Thus, this study reviews the present status and outlines the future trends of PeLED research.

2 Criterion for statistics

All data in the following figures and tables are extracted from reported studies that were published before April 2020. Of note, standard certification for LEDs has not been adopted to evaluate the performance of PeLEDs [9]. Herein, peak EQE is used to rank the PeLED efficiency regardless of the errors between different measurement

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systems. For the operation stability, superior devices and competitive cases are shown despite different test conditions. A compromised rule is developed to distinguish the emission color of PeLEDs as follows: electroluminescence (EL) peak shorter than 500 nm is blue, 510–540 nm is green, 630–700 nm is red, and beyond 750 nm is near-infrared.

3 Performance tables

Classified according to the EL peak, Table 1 lists the best-performing PeLEDs in different emission bands. The columns include color, perovskite composition, dimensionality, EL peak, device structure, EQE, maximum luminance (L_{max}), current efficiency, stability, active area, full width at half maximum (FWHM), CIE coordinate, note, and publication date. We attempted to make this table current and comprehensive by recording all notable studies on solution-processed lead-based PeLEDs. In addition, special cases are also recorded such as optical out-coupling enhancement. The stability and luminance records are separately noted irrespective of the EQE value.

Of note, perovskites in Table 1 are all fabricated by spin coating, which is facile for manufacturing in a laboratory. We insist that vacuum deposition also shows considerable advantages in perovskite film processing (e.g., absence of solubility limit, good reproducibility with uniform morphology, and scaled-up production [10]), which makes it a competitive fabrication technique for the potential commercialization of PeLEDs. Table 2 lists several PeLEDs produced by vacuum methods, which include thermal evaporation (co-evaporation or layer-by-layer deposition), chemical vapor deposition (CVD), and vacuum-assisted multi-deposition. There is only one report on vacuum-deposited blue or red PeLEDs; more attention is dedicated to green PeLEDs. After approximately three years, the EQEs of vacuum-fabricated LEDs gradually exceeded 4%; however, these values are still considerably lower than those of solution-processed PeLEDs.

Finally, Table 3 shows lead-free LEDs to demonstrate environmentally friendly candidates without the toxic heavy metal. Only several studies incorporated lead-free perovskites or perovskite derivatives into LEDs, with the best EQE of 3.8%. However, there have been many lead-free materials with good photoluminescence properties reported in the literature [46–50], which enables further EQE and luminance improvement of lead-free LEDs. In addition, the FWHM of lead-free PeLEDs is several times wider than that of lead-based PeLEDs, which make them more suitable for lighting instead of display applications.

After compiling the performance of state-of-the-art PeLEDs, we further subdivide perovskite categories into three parts by dimensionality (Fig. 1). From the material point of view, dimensionality engineering has been widely adopted. Low-dimensional perovskites with a larger exciton binding energy show enhanced radiative recombination and higher EQE [62]. Therefore, we summarized the highest EQEs (Fig. 1(a)) and luminance (Fig. 1(b)) of bulk, quasi-two-dimensional (quasi-2D), and quantum dot (QD) PeLEDs with conventional device architectures apart from out-coupling strategies.

4 What lies behind the statistics

Metal halide perovskites possess considerable potential in LED applications. The EQEs of green, red, and near-infrared PeLEDs have reached over 20%, which is comparable to those of commercial OLEDs. In addition, the FWHM of PeLEDs is narrower than that of OLEDs, which indicates a more saturated color gamut in the National Television System Committee (NTSC) standard. This rapid and exciting progress attracts and encourages more researchers toward this rising field, as indicated by the upsurge in published papers in this field. With more institutions and researchers delving into this field, the performance, stability, and manufacturability of PeLEDs can be hopefully pushed to surpass those of OLEDs in the near future, which enables their display and lighting applications.

Operation stability is the major existing challenge. The reported lifetime of PeLEDs lags far behind that of OLEDs and QLEDs, which impedes their commercialization. With an increase in the device EQE, stability is the major drawback that must be solved. Strategies to enhance stability will be aided by researching the following aspects: intrinsic instability of perovskite materials and degradation mechanism of PeLEDs, which require meticulous and systematic exploration.

Efficient blue PeLEDs with a synergetic EL stability enhancement deserve more efforts. The relatively poor performance of blue PeLEDs originates from unsatisfactory EQE and inferior operation stability. Blue emitters can be achieved by mixed halide perovskites, which always undergo EL redshift stemming from phase segregation. Blue PeLEDs from reduced-dimensional perovskites suffer from the inefficiency of electrically-driven carrier injection and difficulty of single-phase control. Exploring ways to produce efficient and stable blue PeLEDs is an essential and challenging subject that must be addressed in the future.

Efficiency-oriented exploration of new materials and process methods requires further studies. As discussed above, solution-processed Pb-based PeLEDs have been considerably improved in the past few years; however, the high toxicity of lead and relatively low reproducibility cast doubt on their potential commercialization. Electroluminescent devices that are based on lead-free perovskites or perovskite derivatives are one direction that is worth further exploration. The other worthwhile direction is to identify more commercially viable fabrication strategies.

Table 1 Performance list of PeLEDs with record EQEs for different emission bands

color	perovskites	dimensionality	EL /nm	device structure	EQE /%	L_{max} /(cd·m^{-2})	current efficiency /(cd·A^{-1})	stability	area /cm^2	FWHM /nm	CIE	note	publication date
blue	$CsPbBr_3$:PEACl:2%YCl_3 [6] ($CsPbBr_3$:PEACl:10% YCl_3)	quasi-2D	485 (477)	glass/ITO/PEDOT:PSS/perovskite/TPBi/LiF/Al	**11.8** (4.8)	**9040** (~6000)	NA	L_0 = 100 cd/m^2@3.2 V, T_{50}~100 min spectral stability: 120 min@3.2 V; negligible spectrum variation under varied biases	0.1	NA	(0.09, 0.19) ((0.10, 0.13))	stable bright	Dec. 2019
	$PBABr_{1.1}(Cs_{0.7}FA_{0.3}PbBr_3)$ [7]	quasi-2D	483	glass/ ITO/NiO_x/TFB/PVK/perovskite/TPBi/LiF/Al	9.5	~700	~12	L_0 = 100 cd/m^2@1 mA/cm^2, T_{50}~250 s spectral stability: ~1600 s@ 0.2 mA/cm^2; shape of the EL spectrum does not change at increasing bias up to 6 V	0.0324	26	(0.094, 0.184)		Aug. 2019
	$CsPbCl_{0.9}Br_{2.1}$ + 100% PEABr [11]	quasi-2D	480	glass/ITO/PEDOT:PSS/perovskite/TPBi/LiF/Al	5.7	3780	6.1	T_{50} (EQE drops to 50% of its initial value) = 10 min@4.4 V spectral stability: 1 min@4.4 V; increasing voltage, the spectrum is stable from 3.6 to 5.6 V, exceeding 6 V, spectrum red shifted slightly by around 8 nm	0.1	21	(0.102, 0.178)		Mar. 2019
	$BA_2Cs_{n-1}Pb_n(Br/Y)_{3n+1}$ [12]	quasi-2D	465 (487)	glass/ITO/PEDOT:PSS/PVK/perovskite/TPBi/Al	2.4 (6.2)	962 (3340)	NA	T_{70} (EQE drops to 70% of its initial value) ~10 min spectral stability: 5 min@6 V (78 mA/cm^2) (15 min@7 V, 35 mA/cm^2)	NA	23 (22)	NA		Jan. 2019
	$PEA_2Cs_{1.6}MA_{0.4}Pb_3Br_{10}$ DPPOCl [13]	quasi-2D	479 (489)	glass/ITO/PEDOT:PSS/PFI/perovskite/TPBi/LiF/Al	5.2 (1.3)	468 (5141)	NA	L_0 = 100 cd/m^2, $\boldsymbol{T_{50}}$ **= 90 min** spectral stability: wavelength shift is zero between half and maximum luminance (L_0 = 1500 cd/m^2, T_{50} = 51 min@50 mA/cm^2)	0.0614	18	NA	stable	Mar. 2020
	(Cs/Rb/FA/PEA/K)Pb$(Cl/Br)_3$ [14]	quasi-2D	484	glass/ITO/LiF/perovskite/LiF/Bphen/LiF/Al	2.01	4015	2.11	L_0 = 80 cd/m^2, $\boldsymbol{T_{50}}$ **= 300 min**@25 mA/cm^2 EL wavelength undergoes a red shift of about 8 nm after continuous operation at 25 mA/cm^2 for a period of time	0.12	~24	(0.135, 0.198)	stable	Feb. 2020
	$PEA_2(Rb_{0.6}Cs_{0.4})_2Pb_3Br_{10}$ [15] $PEA_2(Rb_{0.4}Cs_{0.6})_2Pb_3Br_{10}$	quasi-2D	475 (490)	glass/ITO/PEDOT:PSS/perovskite/TmPyPB/LiF/Al	1.35 (1.48)	100.6	NA	L_0 = 15 cd/m^2@4.5 V, $\boldsymbol{T_{50}}$ **= 14.5 min**; spectral stability: EL spectra changes negligibly under continuous operation for 20 min. (**$\boldsymbol{T_{50}}$ = 18.7 min**@4 V)	NA	20	(0.115, 0.099)	stable	Aug. 2019
	Ca-TPBO-$CsPbBr_xCl_{3-x}$ [16]	QD	**463**	glass/ITO/PEDOT:PSS/TFB/PFI/perovskite/TPBi/LiF/Al	**3.3**	569	NA	NA	NA	17	NA		Mar. 2020
	P-$PDABr_2$-Cs $PbBr_3$ [17]	quasi-2D	465	ITO/PVK/PFI/perovskite/TPYMB/Liq/Al	2.6	211	NA	T_{50} = 13.5 min@peak EQE (0.35 mA/cm^2)	NA	25	(0.145, 0.05)		Sep. 2019

(*Continued*)

color	perovskites	dimensionality	EL /nm	device structure	EQE /%	L_{max} /(cd·m^{-2})	current efficiency /(cd·A^{-1})	stability	area /cm^2	FWHM /nm	CIE	note	publication date
green	quasi-core/shell $CsPbBr_3$/ MABr (mixture 1.0) [3]	3D	525	glass/ITO/PEDOT: PSS/perovskite/ PMMA/B3PYMPM/ LiF/Al	20.3	14000	78	L_0 = 7130 cd/m^2, T_{50}~10.42 min@167 mA/cm^2; estimating T_{50} at 100 cd/m^2 to be about 100 h	0.03	20	(0.18, 0.75)		Oct. 2018
	$CsPbBr_3$ + PEABr + PEG [19]	quasi-2D	514	glass/ITO/ZnO/ PEDOT:PSS/perovskite/TPBi/LiF/Al	**28.2**	~10^4	88.7	NA	0.1	18	(0.088, 0.764)	out-coupling	Apr. 2019
	$CsPbBr_3$ + PEABr + PEG [19]	quasi-2D	512	PET/Ag NWs/pattern ZnO/ETA-PEDOT/ perovskite/TPBi/LiF/ Al	24.5 (17)	~10^4	75	L_0 = 100 cd/m^2, T_{50}~7.56 h	0.1	NA	(0.079, 0.751)	out-coupling flexible	Mar. 2020
	$MAPbBr_3$:TPBi [20]	3D	540	glass/self-organized conducting polymer (SOCP) anode/perovskite/TPBi/LiF/Al	21.8	NA	87.35	L_0 = 100 cd/m^2, T_{50} = 250 min	NA	NA	NA	out-coupling	Apr. 2019
	TFA-derived $CsPbBr_3$ [21] ($FA_{0.11}MA_{0.10}Cs_{0.79}PbBr_3$)	3D	518	glass/ITO/PEDOT: PSS/perovskite/ TPBi/LiF/Al	10.5 (17)	16436 (35700)	32	L_0 = 100 cd/m^2, $\boldsymbol{T_{50}}$ **= 250 h**	NA	NA	NA	stable	Feb. 2019
	$CsPbBr_3$-PEO-CF [22]	3D	525	glass/ITO/PEDOT: PSS/perovskite/ TPBi/LiF/Al	4.76	51890	NA	under ambient conditions (relative humidity ~60%), $\boldsymbol{L_0}$ **≈ 1000 cd/m^2**, $\boldsymbol{T_{82}}$ **= 80 h**	0.0725	20	NA	stable	May. 2017
	KBr-$CsPbBr_3$ [23]	3D	~520	glass/ITO/ Poly-TPD/PVK/perovskite in SiO_2 aperture (100 nm)/TPBi/LiF/Al	7.7	**7646206**	NA	NA	NA	NA	NA	bright	Apr. 2020
	$CsPbBr_3$ [24]	3D	523	glass/ITO/a-ZSO/ perovskite/NPD/ MoO*x*/Ag	9.3	**496320**	37	NA	NA	16	NA	bright	Jul. 2019
red	CsPb(Br/I)$_3$ [5]	QD	653	glass/ITO/PEDOT: PSS/poly-TPD/perovskite/TPBi/Liq/Al	21.3	500 (794)	10.6	L_0 = 100 cd/m^2,T_{50} = 5 min@1.25 mA/cm^2 (for An-HI-based LED, T_{50} = 180 min)	0.02	33	(0.72, 0.28)		Oct. 2018
	FPMATFA-$FA_{0.33}Cs_{0.67}Pb(I_{0.7}Br_{0.3})_3$ [25]	3D	694	glass/ITO/poly-TPD/ perovskite/TPBi/LiF/ Al	20.9	~400 (10^2)	NA	in N_2 glove box, L_0 = 25 cd/m^2, $\boldsymbol{T_{50}}$ **= 14 h@2.5 mA/cm^2**	0.04	37	(0.732, 0.268)	stable	Feb. 2020
	PEDXA-$CsPbBr_{0.6}I_{2.4}$ [26]	3D	668	glass/ITO/ZnMgO/ perovskite/poly-TPD/MoO_3/Ag	6.55	338	1.36	$\boldsymbol{L_0}$ **= 300 cd/m^2**, $\boldsymbol{T_{50}}$ **= 0.5 h.** no change in EL spectra was observed at different applied voltages	NA	32	(0.726, 0.274)	stable	Nov. 2018
	Zr-$CsPbI_3$ [27]	QD	686	Si/Ag/ZnO/PEI/perovskite/TCTA/ MoO_3/Au	13.7	14725	NA	efficiency drop ~8.7% under 500 mA/cm^2	NA	NA	(0.71, 0.28)	stable	Mar. 2020

(*Continued*)

color	perovskites	dimensionality	EL /nm	device structure	EQE /%	L_{max} /(cd·m^{-2})	current efficiency /(cd·A^{-1})	stability	area /cm^2	FWHM /nm	CIE	note	publication date
	4-F-PMAI-$CsPbI_3$ ($CsPbI_{2.8}Br_{0.2}$) [28]	QD	692 (689)	ITO/poly-TPD/perovskite/TPBi/LiF/Al	14.8 (18.6)	NA	NA	L_0 = 100 cd/m^2, T_{50} ~20 h@5 mA/cm^2	0.04	36	(0.72, 0.27)	stable	Mar. 2020
	$CsPbBrI_2$ [24]	3D	650	glass/ITO/a-ZSO/perovskite/NPD/MoO_x/Ag	4.6	20000	2.5	NA	NA	40	NA	bright	Jul. 2019
near-infrared	ODEA-$FAPbI_3$ [29]	3D	800	glass/ITO/ZnO:PEIE/perovskite/TPB/MoO_x/Au	21.6	NA	NA	in the glovebox without encapsulation, T_{50} (EQE drops to its 50%) = 20 h@25 mA/cm^2	0.0725	NA	NA		Mar. 2019
	5AVA-$FAPbI_3$ [2]	3D	803	glass/ITO/PEIE-ZnO/perovskite/TPB/MoO_3/Au	20.7	NA	NA	with glass-epoxy encapsulation, T_{50} = 20 h@100 mA/cm^2	0.03	75 meV	NA		Oct. 2018
	perovskite-polymer ($(NMA)_2(FA)Pb_2I_7$-poly-HEMA) [30]	quasi-2D	~795	glass/ITO/MZO/PEIE/perovskite/TPB-PFO/MoO_x/Au	20.1	NA	NA	encapsulated with epoxy adhesive/cover glass in air, the EL half-life T_{50} = 46 h@peak EQE (0.1 mA/cm^2)	NA	~49	NA		Nov. 2018
	5-AVA-$FAPbI_3$ [31]	3D	799	glass/ITO/ZnO/PEIE/perovskite/poly-TPD/MoO_3/Al	20.2 (12.1)	NA	NA	T_{80} = 20 h@peak EQE (57 mA/cm^2) (large-area T_{50} = 10 h@10 mA/cm^2	0.04	41	NA	large-area (9 cm^2)	Apr. 2020
	$(PEA)_2PbI_4$-$FA_{0.98}Cs_{0.02}PbI_3$ [32]	2D/3D	~810	glass/ITO/ZnO nanoparticle/perovskite/poly-TPD/MoO_3/Ag	NA	NA	NA	$L_0 \approx$ 10 W/(sr·m^2), after 100 h, it is ≈135% of initial radiance, estimating **T_{50}>200 h**	NA	NA	NA	stable	Feb. 2020

Notes: NA—not available. L_0—initial luminance. $T_{50/80}$—time when L_0 (or EQE) decreases to 50% or 80% of its initial value

Table 2 Performance list of vacuum deposited PeLEDs

color	perovskite	dimensionality	method	device structure	EL /nm	L_{max} /(cd·m^{-2})	current efficiency /(cd·A^{-1})	EQE /%	publication date
blue	Cs-Pb-Br-Cl [33]	3D	co-evaporation	ITO/NiO$_x$/perovskite/TPBi/LiF/Al	468	121	0.21	**0.38**	Nov. 2019
green	$MAPbBr_3$ [34]	3D	vacuum evaporated $PbBr_2$ + CVD MABr	ITO + PFN-OX/perovskite/MoO_3/Au	532	560	NA	0.016	Jun. 2017
	$CsPbBr_3$ [35]	3D	co-evaporation	ITO/PEDOT/poly-TPD/perovskite/TmPyPB/Liq/Al	520	57.65	5.75	1.55	Jul. 2017
	PEA-$MAPbBr_3$ [36]	quasi-2D	layer-by-layer deposition	ITO/PEDOT/perovskite/TPBi/Liq/Al	531	6200	1.3	0.36	Oct. 2017
	$CsPbBr_3$ [37]	3D	vacuum evaporated $PbBr_2$ + dipping CsBr	ITO/ZnO/perovskite/NiO$_x$/Au	522	NA	NA	NA	Apr. 2018
	$CsPbBr_3$ [38]	3D	CVD	Au/MgO/perovskite/n-MgZnO/n$^+$-GaN	538	5025	1.92	1.46	Sep. 2018
	$CsPbBr_3$ [39]	3D	co-evaporation	ITO/PEDOT/perovskite/TPBi/LiF/Al	519	53486	NA	2.5	Feb. 2019
	$CsPbBr_3$ [40]	3D	layer-by-layer deposition	ITO/PVK/perovskite/TPBi/LiF/Al	525	904	NA	0.3	Mar. 2019
	$CsPbBr_3$ [10]	3D	co-evaporation	ITO/NiO$_x$/perovskite/TPBi/LiF/Al	516	9442	10.15	3.26	Oct. 2019
	$CsPbBr_3$ [41]	3D	co-evaporation	ITO/PEDOT:PSS/perovskite/TmPyP8/Lq/Al	524	1607	1.07	NA	Jan. 2020
	PEA-$CsPbBr_3$ [42]	3D	layer-by-layer deposited $CsPbBr_3$ + spin-coated PEABr	ITO/PEDOT:PSS/perovskite/TPBi/LiF/Al	529	5684	14.64	**4.1**	Mar. 2020
red	$CsSnBr_3$ [43]	3D	layer-by-layer deposition	ITO/LiF/perovskite/LiF/ZnS/Ag	672	172	0.65	0.34	Mar. 2018
near-infrared	MAPb(I/Br)$_3$ [44]	3D	dual-source evaporated $MAPbI_3$ + evaporated $PbBr_2$ + spin-coated MABr	ITO/PEDOT/poly-TPD/perovskite/PCBM/Ba/Ag	**784**	~300	NA	0.06	Sep. 2015
	$MAPbI_3$ [45]	3D	co-evaporation	ITO/C_{60}/perovskite/TaTm/Au	760	NA	NA	**1.92**	Sep. 2018

Table 3 Performance list of lead-free LEDs

color	method	perovskite	EL /nm	device structure	EQE /%	current efficiency /(cd·A^{-1})	L_{max} /(cd·m^{-2})	FWHM/nm	publication date
near-infrared	spin-coating	$CH_3NH_3Sn(Br_{1-x}I_x)_3$ [51]	945	ITO/PEDOT:PSS/perovskite /F8/Ca/Ag	0.72	NA	NA	130 meV	Jun. 2016
near-infrared	spin-coating	$CsSnI_3$ [52]	950	ITO/PEDOT/perovskite/PBD/LiF/Al	3.8	NA	NA	> 100	Jul. 2016
red	spin-coating	PEA_2SnI_4 [53]	618	ITO/PEDOT:PSS/perovskite/F8/LiF/Al	NA	0.029	0.15	~50	Jun. 2017
red	layer-by-layer deposition	$CsSnBr_3$ [43]	672	ITO/LiF/$CsSnBr_3$/LiF/ZnS/Ag	0.34	0.65	172	~54	Mar. 2018
blue	spin-coating	$Cs_3Cu_2I_5$ [54]	440	ITO/ZSO/$Cs_3Cu_2I_5$/NPD/MoO_x/Ag	NA	NA	10	> 70	Sep. 2018
white	layer-by-layer deposition	$Cs_2Ag_{0.6}Na_{0.4}InCl_6$ [55]	560	glass/PEIE-ITO/PEIE-ZnO/perovskite/TAPC/ MoO_3/Al	NA	0.11	~50	~170	Nov. 2018
orange	spin-coating	$(C_{18}H_{35}NH_3)_2SnBr_4$ [56]	621	ITO/ZnO/PEI/perovskite/TCTA/MoO_3/Al	0.1	NA	350	~163	Jan. 2019
near-infrared	vapor-anion-exchange	$Cs_3Sb_2I_9$ [57]	> 750	ITO/PEDOT/perovskite/TPBi/LiF/Al	NA	NA	NA	> 120	Aug. 2019
violet	spin-coating	$Cs_3Sb_2Br_9$ [58]	408	ITO/ZnO/PEI/perovskite/TCTA/MoO_3/Al	0.206	NA	29.6	~70	Feb. 2020
red	spin-coating	PEA_2SnI_4 [59]	633	ITO/PEDOT:PSS/perovskite/TPBi/LiF/Al	0.3	NA	70	24	Mar. 2020
yellow	spin-coating	$CsCu_2I_3$ [60]	550	ITO/PEDOT:PSS/poly-TPD/perovskite/TPBi/ LiF/Al	0.17	NA	47.5	~100	Mar. 2020
blue	spin-coating	$Cs_3Cu_2I_5$ [61]	445	ITO/P-NiO/perovskite/TPBi/LiF/Al	1.12	NA	263.2	~63	Apr. 2020

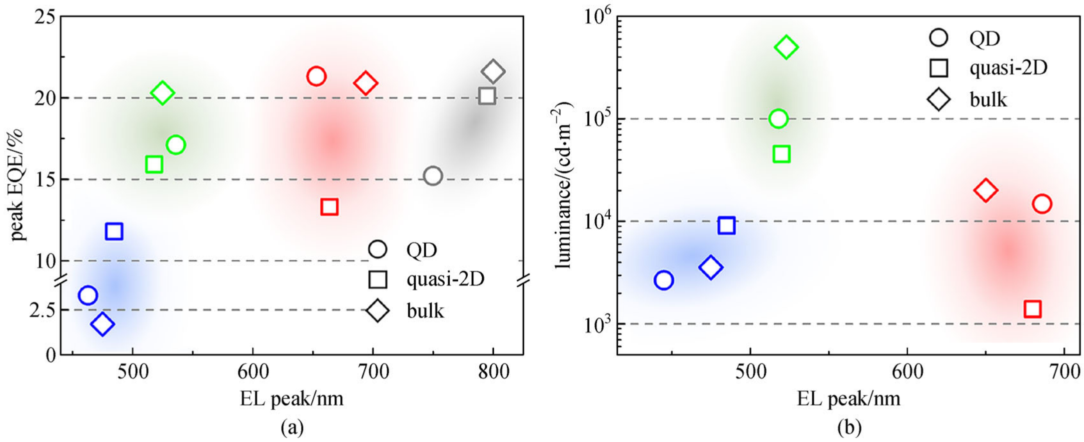

Fig. 1 (a) Best EQEs [3,5,6,16,25,29,30,63–67] and (b) highest luminance [6,24,27,63,68–71] of bulk, quasi-2D, and quantum dot PeLEDs

Inkjet printing or electrohydrodynamic printing is the top choice for the fabrication of ultra-large-size displays. Thermal evaporation (preferably single-sourced), which is compatible with existing OLED manufacturing lines, also deserves more research attention. More efforts must be devoted to these new technologies to improve their performance through composition, morphology, grain engineering, and device physics.

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