Linearly polarized photoluminescence from anisotropic perovskite nanostructures: emerging materials for display technology

Yong Ge\textsuperscript{a}, Linghai Meng\textsuperscript{a}, Zelong Bai\textsuperscript{b} and Haizheng Zhong\textsuperscript{a}

\textsuperscript{a}Beijing Key Laboratory of Nanophotonics and Ultrafine Optoelectronic Systems, School of Materials Science & Engineering, Beijing Institute of Technology, Beijing, People’s Republic of China; \textsuperscript{b}School of Aerospace Engineering, Beijing Institute of Technology, Beijing, People’s Republic of China

ABSTRACT

Polarization is an important feature of light, which plays an important role in display technology. Anisotropic semiconductor nanostructures (nanorods, nanoplatelets) show polarized emissions. In this progress report, we summarized the recent research progress of anisotropic perovskite nanomaterials for potential liquid crystal display backlight, with focus on the fabrication and assembly. Finally, the paper points out the bright future of using perovskite nanostructures for display technology.

1. The application of anisotropic materials in display technology

Polarized light plays an important role in modern optoelectronic devices such as liquid crystal display (LCD) backlight [1,2], 3D display systems [3] and polarization photodetection [4,5]. The polarization ratio is a parameter that can measure the degree of polarization, which can be defined as [6]

\[ P = \frac{I_\parallel - I_\perp}{I_\parallel + I_\perp} \]  

where \( P \) is the polarization ratio, \( I_\parallel \) and \( I_\perp \) represent the emission intensity parallel and perpendicular to the alignment direction, respectively. In LCD systems, the vertical polarizer filters are widely used to generate polarized light. The process of generating polarized light will decrease the brightness of backlight, causing the loss of energy [7]. The use of polarized light source can improve the energy efficiency, thus the fabrication and application of luminescence materials as polarized light source have attracted great interest of both of material science and optical engineering.

Colloidal quantum dots (QDs) show advantageous properties of strong blue light absorption, tunable photoluminescence (PL) emission, high quantum yields, and easy solution processability [8,9], which have been applied in commercial television to enhance the color performance (for example, the CdSe based QDs enhancement film by 3M and Nanosys). In addition to the excellent PL features, the anisotropy nanomaterials promise emission and excitation polarization [10,11]. Recently, Talapin’s group’s and Rogach’s group envisioned replacing spherical QDs with one-dimensional nanomaterials such as nanorods and nanowires to achieve enhanced brightness [1,2].

Compared with II-VI QDs, the newly developed perovskite quantum dots (PQDs, CH\(_3\)NH\(_3\)PbX\(_3\) (MAPbX\(_3\)) and CsPbX\(_3\), X = Cl, Br, I) show advantages of narrower full width at half maximum (FWHM), low fabrication cost, most importantly, the ease of room temperature or in situ preparation [12,13]. The scale-up fabrication of in situ fabricated PQDs composite polymer films (PQDCF) has been developed by Zhijing Nanotech and Lucky cooperation, and they work with TCL to demonstrate the first PQDCF integrated LCD backlights [14]. In CES 2018, TCL published the first PQDCF based 55” TV panel with a color gamut of 101% and a highest brightness of 500 nits. Compared with QDs, the anisotropic structure of anisotropic perovskites nanocrystals (APNCs) also shows optical anisotropy such as emission polarization [15,16]. By orienting into aligned arrays and integrated in LCD backlight, the polarized light can be obtained, improving the energy efficiency in LCD
backlight. As shown in Figure 1, in a typical LCD system, we need a vertical polarizer in order to obtain linearly polarized light. If we use aligned APNCs as the backlighting unit and replace the quantum dot film, the partial polarized light can be obtained, reducing the energy loss when passing through the polarizer filter. The fabrication and alignment of APNCs are crucial for its application. In this progress report, we will summarize the recent development of preparation and alignment of APNCs and the investigation of its polarization features, which might be a guidance for the energy saving and brightness enhancement of LCD.

2. The fabrication of APNCs

In recent years, many strategies have been developed to obtain APNCs (e.g. nanorods, nanowires). From the viewpoint of materials growth, the fabrication of APNCs can be divided into template and chemical assistant growth.

2.1. Template assisted growth

The template-assisted growth is an efficient way to grow anisotropic perovskite nanorods or nanowires. In the typical process of fabrication, the micropillar-structured template was first prepared by imprint, photoetching or two-step anodization methods [17–19], after that, the perovskite were grown by solution or chemical vapor deposition (CVD) methods. In the process of growth, the confined effect of the template can lead the one-dimensional growth of crystals along the arrays, formatting high-quantity nanowires. As shown in Figure 2(a), Gu et al. [17] fabricated MAPbI₃ nanowire arrays in free-standing porous alumina membrane (PAM) template by vapor–solid–solid reaction (VSSR) process, and a 3 × 3 cm array was obtained, which was used as the active area of a 1024 pixel image sensor. Deng et al. [18] reported a method to produce highly aligned single-crystalline MAPb(1₋ₓBrₓ)₃ (x = 0, 0.1, 0.2, 0.3, 0.4) nanowire (NW) arrays with continuously tunable absorption edges from 680 to 780 nm. Periodically aligned SU-8 photosensitive stripes on the SiO₂/Si substrate was used as the template, and the perovskite NW arrays were fabricated by a fluid-guided antisolvent vapor assisted crystallization (FGAVC) method. The template was first dipped into MAPbI₃/DMF solution and placed in the saturated antisolvent (CH₂Cl₂) vapor. The diffusion of antisolvent lead to the precipitation of CH₃NH₃PbI₃ nanocrystals along the sides of SU-8 photosensitive stripes, the schematic diagram can be seen in Figure 2(b). Liu et al. [19] prepared nanowire arrays using imprinted poly(dimethylsiloxane) (PDMS) as the template, as the evaporation of DMF of MAX and PbX₂ stock solution, the template confinement effect lead to the directional growth of MAPbX₃ along the arrays. Well-defined dimensions and uniform geometries enabled individual PNWs to function as high-quality FP lasers with almost identical optical modes and similarly low lasing thresholds (220 nJ/cm²), allowing igniting them simultaneously as a laser array. The uniform and regular alignment of the APNCs fabricated by template-assisted method appropriate for electronic and photonic devices like laser in on-chip system or detector, but for a display system, the difficulty of large scale alignment of this method limited its application.

Considering the application in LCD backlight, a scale-up preparation method is preferred. Electrospinning is a widely used method of fabricating nano- or micro-scaled fibers, providing a facile and inexpensive process to obtain nanosized polymeric and corresponding composite fibers [20]. By controlling the properties of precursor and process conditions, PNCs embedded polymer nanofibers with polarized emission were fabricated. In the process of the formation of nanofibers, the confinement effect of the nanofibers played an important role in formatting the APNCs, which can be regarded as the 'template' of APNCs. Figure 3(c) shows typical transmission electron microscopy (TEM) images [21,22]. We can clearly see the APNCs were formatted in the matrix of Polyacrylonitrile (PAN) nanofibers. The selection of suitable solvents and polymers is the key to obtain high-quality nanofibers. Except for PAN, poly(styrene–butadiene–styrene) (SBS) [23], poly(styrene (PS) [24], polyurethane (PU) [25] and polyvinyl alcohol (PVA) [21] have been selected as the matrix of perovskites/polymer nanofibers, and tetrahydrofuran (THF), N,N-dimethylformamide (DMF), dimethyl sulfoxide (DMSO) are always selected as the solvent of polymer and perovskite precursor. As shown in Figure 3(a), Lin et al. [23] fabricated CsPbX₃ (X = Cl, Br, I) @ SBS fiber membranes (FMs) via electrospinning method. Benefiting the encapsulation of SBS, the as-fabricated
FMs show water resistance, and a white light-emitting diodes (WLEDs) were fabricated by combining with blue LED chip, showing the promising applications in lighting and display backlights. Tsai et al. [22] fabricated core/shell perovskite nanofibers by a one-step coaxial electrospinning, wherein the perovskite materials (MAX
and PbX₂) and PAN were used as the core and shell precursors, the optimized perovskite nanofiber could yield a high photoluminescence quantum yield (PLQY) of 30.9%. By varying the composition of perovskites, the tunable photoluminescence spectra can be obtained. Moreover, owing to the hydrophobic nature of the shell polymer, the prepared perovskite-based polymer nanofiber was endowed with high ambient stability and a high resistance to water. The electrospinning perovskite nanofibers also show some unique optical properties like emission polarization. Güner et al. [25] fabricated CsPbBr₃ nanowires/PU nanofibers, the aligned electrospin nanofibers showed emission polarization of 0.17 ∼ 0.30. Meng et al. [21] reported an in situ fabrication of halide perovskite/PVA nanofibers, which is more efficient and convenient than the ex-suit methods. By controlling the perovskite precursor solution, the MAPbBr₃ nanocrystals in PVA matrix changed the shape into rod-like, leading to strong emission polarization and the optimized quantum yield up to 72%, and the films of well-aligned MAPbBr₃@PVA nanofibers with a macroscale size of 0.5 × 2 cm can be obtained, showing potential applications in displays, lasers, and waveguides. The low cost and polarization features of PNCs based polymer nanofibers make it suitable candidates as color conversion materials for LCD backlight.

2.2. Chemical assisted growth

The template-assisted growth always need to prepare high-quantity templates, which always decide the features of APNCs. Limited to the scale of templates, the method would not always guarantee the mass production of APNCs. The chemical-assisted growth represents a family of methods that obtain APNCs by adjusting the chemical limitations, such as ligands, precursor concentration, temperature and anion-exchange reaction. As seen in Figure 4(a), Zhou et al. [26] reported a vapor-phase growth of high-quality cesium lead halide micro/nanorods in SiO₂/Si substrates with tunable compositions. The as-fabricated triangle nanorods with triangular cross section can act as high-quality

![Figure 4.](image-url)
Fabry—Perot (FP) cavities to realize high-quality multicolor lasing under laser pumping with very low pumping threshold (\( \sim 14.1 \mu J/cm \)) and high-quality factor (\( \sim 3500 \)), showing the potential for large scale integrated devices. Contrasting to the vapor-phase growth, the solution-phase growth process affords low-temperature solution processing, which can be adjusted by the perovskites precursors. Sichert et al. [27] controlled the thickness and consequently the PL emission of the nanoplatelets (NPLs) by tuning the ratio of the organic thickness and consequently the PL emission of the perovskites precursors. Sichert solution processing, which can be adjusted by the per-solution-phase growth process affords low-temperature devices. Contrasting to the vapor-phase growth, the \( \text{PbAc}_2 \) solid thin film deposited on glass substrate in initiated solution growth strategy using a lead acetate platelet thickness. Zhu et al. [28] developed a surface-initiated solution growth strategy using a lead acetate \( \text{PbAc}_2 \) solid thin film deposited on glass substrate in contact with a high concentration of \( \text{CH}_3\text{NH}_3\text{X}(X = \text{Cl, Br, or I}) \) solution in isopropanol at room temperature. There would be a two-step process for the growth of single-crystal NWs and other nanostructures:

\[
Pb(\text{Ac})_2(s) + 4\text{I}^-(\text{sol}) \rightarrow Pb\text{I}_4^{2-}(\text{sol}) + 2\text{Ac}^-(\text{sol}) \tag{2}
\]

\[
Pb\text{I}_4^{2-}(\text{sol}) + \text{CH}_3\text{NH}_3^+(\text{sol}) \rightarrow \text{CH}_3\text{NH}_3\text{PbI}_3(s) + \text{I}^-(\text{sol}) \tag{3}
\]

They also found the key to successful nanostructure growth is the slow release of the low-concentration Pb precursor \( \text{PbI}_4^{2-} \) from the solid \( \text{Pb(AC)}_2 \) film on the substrate and the careful tuning of the \( \text{CH}_3\text{NH}_3\text{X} \) precursor concentration to maintain a low supersaturation condition for the crystal growth of perovskites. They also synthesized nanowires show very low lasing thresholds (\( 220 \text{ nl/cm} \)) and high-quality factors (\( Q \sim 3600 \)), making it ideal materials for the nanophotonics. Bekenstein et al. [29] synthesized CsPbBr\(_3\) perovskite NPLs by a colloidal method. \( \text{PbBr}_2 \) was solubilized in octadecene (ODE) with oleic acid and oleylamine, and then Cs oleate was injected at elevated temperatures (90–130°C) to form NPLs. By adjusting the reaction temperature, a different shape can be obtained. Reactions conducted at 150°C produce mostly symmetrical nanocubes with green-color PL emission. At 130°C, cyan emitting lower symmetry nanoplates can be obtained, At 90°C and 100°C, very thin NPLs were detected along with lamellar structures ranging 200–300 nm in length. The HRTEM and XRD characteristics are shown in Figure 4(c). The NPLs show high photoluminescence (PLQYs up to 84%). Zhang et al. [30–32] studied the formation mechanism of CsPbX\(_3\) NWs, the reaction dynamics were studied at 150°C. As shown in Figure 4(d), at the reaction time of 10 min, 30 min, 40 min, 90 min, 180 min, the morphology of CsPbBr\(_3\) nanostructures evolved from nanocubes to nanowires, at last, the large crystals. By investigating the influence of temperature, time, surfactants, and precursor concentration, the nanowires formation is owned to a surfactant-directed one-dimensional (1D) growth mode. In order to obtain CsPbX\(_3\) NWs with different wavelength, anion-exchange reactions were used to achieve a wide range of compositions. The alloy NWs have bright and tunable photoluminescence spanning over nearly the entire visible spectral region, which is suitable for display application.

Assembly of functional nanosized materials (semiconductor or metal nanocrystals) into superstructures is the important prerequisite for electronic and optoelectronic applications. For II-VI QDs, the self-assembly has been widely studied [33–35], which is an efficient method to obtain anisotropic nanostructures. It was found that the reaction time, surface ligands and dipole are important factors for formatting anisotropic materials. Liu et al. [16] reported the synthesis of \( \text{CH}_3\text{NH}_3\text{PbI}_3 \) nanoplatelets through self-organization from nanodots. As shown in Figure 5(a), after keeping 3 days at room temperature, the nanodots transformed into nanoplates. It was found that the dipolar vectors are the main factors driving the self-organization process. Additionally, the nanoplates were incorporated into a stretchable polymeric matrix and a polarization emission ratio of 0.11 was obtained, mainly arises from the alignment of NPLs. Pan et al. [36] synthesized CsPbX\(_3\) nanocrystals by in-situ growth method using polyacrylic acid-grafted graphene oxide (GO-g-PAA) as the surface ligand. Upon solvent treatment by the addition of colloidal toluene solution of the CsPbBr\(_3\) NC-GO-g-PAA hybrid into hexane, the self-assembled nanorod-shaped suprastructures formatted. The assembly into nanorods can be understood as a solvent polarity driven process, formed nanorod suprastructures provide excellent encapsulation of the perovskite NCs, which endow extraordinary stability toward protic solvents such as methanol and water. Sun et al. [37] discovered the polar solvent molecules can induce the lattice distortion of ligand-stabilized cubic CsPbI\(_3\), which can initiate the self-assembly of CsPbI\(_3\) nanocubes to nanowires. The TEM images of assembly process can be seen in Figure 5(b). Compared to template-assisted growth, the solution-phased growth of self-assembly strategy promise a mass production of APNCs.

### 3. The alignment of APNCs

The above solution-processed growth of APNCs always obtain disordered materials. Considering the application in optoelectronic devices, many methods have
been developed to align one-dimensional materials for II-VI or noble metal nanorods, such as electric field assisted \[38\], liquid crystal assisted \[39\], template-assisted alignment \[35,40\] or oriented in polymeric matrix \[1\], which can provide references for the alignment of anisotropic perovskite nanostructures. Combining with the unique features of lead halide perovskite such as in situ or low-temperature fabrication \[12,13\], recently, many efforts have been devoted to develop strategies for orienting APNCs, which can be divided into two classes, alignment on substrate and in polymeric matrix.

### 3.1. Alignment on Substrates

The first type of alignment of APNCs is aligning them on glass \[19\], SiO$_2$/Si \[18,26,41,42\] and FTO substrates. Benefited from the low temperature, solution-phase processability of perovskite materials, the fabrication of APNCs always accompanied with the alignment. The template-assisted growth is a common method to obtain perovskite nanorods. By preparing the template with ordered patterns, the aligned nanorods can be obtained during the fabrication process. As shown in Figure 6(a), Liu et al. \[19\] prepared NW arrays using imprinted PDMS as the template. The well-defined dimensions and uniform geometries of nanorod patterns enabled individual PNWs to function of FP nanolasers, and easy to be integrated in photonic circuits. Figure 6(b) shows the TEM images of the nanowire patterns aligned by the PDMS template. Besides template-assisted methods, self-assembly is also a facile method to obtain ordered perovskite patterns. Deng et al. \[41\] fabricated organ lead iodide perovskite NWs by a one-step self-assembly method on SiO$_2$/Si substrates. In the growth process of

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**Figure 5.** (a) Illustration of the transformation of CH$_3$NH$_3$PbBr$_3$ NCs from NDs to NPLs, and the corresponding TEM images of the original NDs and the resultant NPLs \[16\]. Reproduced with permission. Copyright 2016, Wiley-VCH. (b) Schematic diagram and TEM images of self-assembly process of CsPbI$_3$ nanocubes into nanowires \[37\]. Reproduced with permission. Copyright 2018, American Chemical Society.

**Figure 6.** The alignment of APNCs on substrate. (a) Schematic illustration of the preparation procedures of perovskites nanowires (PNW) array. (b) Low- (left), medium- (middle), and high-magnification (right) images of MAPbBr$_3$ PNW arrays \[19\]. Reproduced with permission. Copyright 2017, American Chemical Society. (c) Schematic description for the aligned NW growth. Evaporation direction was pointed out by arrows. (d) Optical images of NWs grown by modified EISA method. (e) Growth products synthesized from different concentrations of 45 and 10 wt% \[41\]. Reproduced with permission. Copyright 2015, Royal Society of Chemistry.
perovskite NWs, the substrates were tilted to a small angle ($\sim 10^\circ$) for the controllable distribution of nanowires, the schematic description for the aligned NW growth by evaporation-induced self-assembly (EISA) was shown in Figure 6(c). Figure 6(d,e) shows the optical images of NWs grown by modified EISA method with different concentrations, the decreasing concentrations resulted in the decreased number of layers and diameters. The aligned APNCs showed its promising use in lasers and photodetectors.

### 3.2. Alignment in polymer matrix

The nanocrystals (NCs)/polymer composite has been investigated over the past decades [13,43–46]. By confining the NCs into polymer matrix, the intrinsic unstable properties of moisture and oxygen can be attenuated, which is suitable for display application. For anisotropic nanocrystals, the polymeric matrix can also help to align anisotropic materials and afford some unique optical properties like polarization. For II-VI nanocrystals, Cunningham et al. [1] oriented CdSe/CdS nanorods and colloidal CdSe nanoplatelets in poly butyl-co-isobutyl methacrylate (PBiBMA) by stretching method, the polarization emission ratio of the film can up to 0.6. Aubert et al. [47] oriented CdSe/CdS nanorods in aligned polyvinylpyrrolidone (PVP) nanofibers, the polarization ratio of aligned PVP nanofibers was found to be 0.45. For perovskite nanomaterials, the in-situ fabrication features make it easier to be obtained. Lu et al. [48] stretched MAPbBr$_3$/PVDF polymer composite films via in situ fabrication process in two time nodes corresponding to the crystallization of PVDF and perovskite nanocrystals, the schematic diagram of crystallization process and stretched films at time node 1 and 2 can be seen in Figure 7(a). By applying the TEM characterization, after stretching, the stretched films showed a microstructure of aligned ‘QD-aligned wires.’ The potential use of these composite films in LCD backlights can increase the light transmittance of polarizers in LCD panel from 50% to 65% with low cost. He et al. [49] reported an in situ catalyst-free strategy to synthesize CsPbBr$_3$ nanorods in a polystyrene (PS) matrix. After stretching, the nanorods can align in the matrix. Electrospinning is an efficient way to get polymeric nanofibers [20,50]. By aligning the nanofibers into ordered patterns, the large scale polarization film can be obtained. Meng et al. [21] aligned MAPbBr$_3$@PVA nanofibers by collecting nanofibers on a high-speed rotating drum, a large area film of 56 cm$^2$ was fabricated. By varying the halogen constitutions, MAPbX$_3$@PVA nanofiber films can also be fabricated, showing the potential to apply as the optical films in LCD backlight.

### 4. Polarization features of APNCs

Polarization is an important feature of light, which has been applied in LCD display and polarization-dependent photonic devices. The polarization features of anisotropic nanocrystals have been investigated in II-VI semiconductor nanorods [10,51,52], nanowires [53] and noble metal nanorods [54,55]. For II-VI semiconductor nanorods, the emission and absorption polarizations...
have been investigated, by synthesizing rod-in-rod heterostructures, the single-particle PL polarization can up to 0.82 [10]. Wang et al. [35] fabricated CdSe/CdS needle-like superparticles by self-assembly and aligned into unidirectional line patterns on Si$_3$N$_4$ substrates, the typical polarization emission ratio up to 0.88, which is higher than the single nanorods. The high emission polarization from CdSe/CdS nanorods always be attribute to the dielectric contrast between the nanorods and the surrounding environment, and the influence from exciton fine structure. For anisotropic perovskite nanostructures, the strategy to obtain high polarization is still under investigation.

4.1. Polarization features of single particle

Wang et al. [15] firstly discovered the emission polarization from CsPbX$_3$ perovskite QDs. By varying the halide component, CsPbX$_3$ (X = Br, I, and mixed halide systems Br/I) can be synthesized by the hot-injection method. Figure 8(a) shows the TEM images of CsPbBr$_3$, CsPbBr$_{1.5}$I$_{1.5}$ and CsPbI$_3$, the CsPbBr$_3$ perovskite belongs to the cubic crystal structure, because of the bigger iodine atoms in CsPbI$_3$, leading to the distortion from cubic structure. The resulting asymmetrical structure would be responsible for the emission polarization. Figure 8(b) shows the emission polarization

Figure 8. The polarization features of single perovskite particle. (a) TEM images of CsPbBr$_3$, CsPbBr$_{1.5}$I$_{1.5}$ and CsPbI$_3$. (b) Polarization properties of the CsPbI$_3$ perovskite and all the perovskite samples in hexane [15]. Reproduced with permission. Copyright 2016, Royal Society of Chemistry. (c) Structure characterizations of CsPbX$_3$ nanowires (NWs) grown on mica by van der Waals (vdW) epitaxy. (d) PL spectra of CsPbBr$_3$ NWs excited by 405 nm laser with thicknesses of $\approx 15$ nm (red lines) and $\approx 250$ nm (olive lines) and corresponding polar diagrams [56]. Reproduced with permission. Copyright 2018, Wiley-VCH.
4.2. Polarization features of aligned 1D APNCs

In order to get macroscopic polarization light source, many strategies have been developed to align nanorods or nanowires. The most efficient and low cost way to get large scale light source for display application is aligned in polymer matrix. The matrix not only oriented APNCs, but also providing efficient protection against water and oxygen in the air for nanocrystals [57,58]. Stretching of polymer matrix [48,49] and electrospinning [21–25,59] are the most frequently used methods to get aligned APNCs in polymer matrix. For stretching method, Lu et al. [48] stretched in-situ fabricated MAPbBr3/PVDF composite film and investigated the polarization features of this film. After stretching, the nanocrystals in the films assembled into ‘QD-aligned wires,’ which exhibit different relative dielectric constant contrast to the surrounding environment. For nanowires with diameter much smaller than the wavelength of excitation light, the internal electric field perpendicular to the long axis is attenuated from the external electric field whereas the internal electric field parallel to the long axis remainsthesameastheexternal electric field. The intensity ratio of internal field perpendicular and parallel to the long axis can be expressed by:

\[
\frac{E_\perp}{E_\parallel} = \frac{2\varepsilon_0}{\varepsilon + \varepsilon_0}
\]

Where the \( \varepsilon \) and \( \varepsilon_0 \) represent the dielectric constants of nanomaterials and the surrounding environment. The change of electric field lead to the emission anisotropy [21,61]. The excitation polarization is also investigated. As shown in Figure 9(c), the PL intensity of composite film is almost independent from the angle of polarization excitation light, which is different from the II-VI semiconductor nanomaterials. For nanofibers fabricated by electrospinning method, Meng et al. [21] adapted a physical model of the dielectric confinement effects and quantum confinement effects in nanofibers. The incident circular polarized light is modulated into elliptic
polarized light due to the change of dielectric constant ($\epsilon$) at the interface of PVA nanofiber and air and then interact with embedded anisotropic PNCs to generate excitons. As shown in Figure 9(d), after the process (i) and process (ii), the polarized emission can be obtained. They also find the polarization anisotropy of emission obtained from single nanofiber based on experimental measurements is slightly larger than the calculated values, which can be explained by the enhanced polarization due to the quantum confinement effects. By aligning on a high-speed rotating drum, a large area film of 56 cm$^2$ can be obtained, showing the promising application in display technology. In Table 1, we summarized the representative emission polarization features of anisotropic perovskite, we can see for perovskite nanoparticles, the highest emission polarization is 0.78, which is synthesized by vapor-phase van der Waals epitaxial method. For macroscopic polarization, a strong emission polarization of 0.33 can be obtained. If we integrate the polarized emission films in LCD backlights, the efficiency and brightness of LCD can be significantly improved. The efficiency of the light transmittance of polarizers in LCD panel can be calculated by:

$$E = \frac{1 + P}{2}$$

where $E$ is the efficiency and $P$ is the polarization ratio of the backlight. By using the film with emission polarization of 0.33, the efficiency can increase from 0.5 to 0.65. More recently, Lewis and Alivisatos et al. report the polarization emission from patterned perovskite nanowires embeded block copolymer [61]. The 3D printing technique is very versatile for achieving different color patterns and gives a excellent polarization ratio of 0.48. The method open up the possibility to integrate them into display, data storage, encryption, and sensing technology.

5. Conclusion and outlook

In conclusion, this minireview summarizes recent research progress on fabrication, alignment and polarization application of APNCs. Benefiting from the low-temperature solution-phase processability or in-situ fabrication of perovskite, the fabrication of perovskite nanowires or nanorods is more convenient than other nanomaterials emitters. With the development of aligning techniques, large scale anisotropy PNC patterns can be obtained, showing promising use in large scale polarization light source for display technology. The perovskite nanowire arrays have been explored as nanolasers or photodetector on integrated devices. For polarization emission application, the alignment of anisotropic perovskite nanocrystals in polymer matrixes have a great potential application in LCD backlight because of high PLQYs, high macroscopic emission polarization and stability from polymer encapsulation. The highest polarization emission ratio of macroscopic film is 0.42, currently. Further exploration of APNCs can focus on the bottlenecks for protentional application, such as alignment control, scale-up fabrication and photonic integration. We believe the investigation of APNCs will be beneficial to not only LCD backlight, but also to other display technology such as OLEDs, 3D display, etc.

Disclosure statement

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Notes on contributors

Yong Ge received his B.S. degree (2016) from School of Material Science and Engineering of Nanjing University of Science and Engineering, China, where he is now an M.S. degree candidate of Beijing Institute of Technology, China. His main research focused on the fabrication, application and optical properties of anisotropy nanomaterials, particularly polarization features.

Linghai Meng received his B.S. degree (2007) and M.S. degree from School of Physics of Hebei University, China, where he is now a Ph.D. candidate of Beijing Institute of Technology, China. His research interests focus on perovskite and its application on optoelectronic devices.

### Table 1. Emission polarization of anisotropy lead halide perovskites.

| Materials | Excitation Wavelength | Emission Wavelength | Emission Polarization |
|-----------|-----------------------|---------------------|----------------------|
| CsPbI$_3$ (in Hexane) [15] | 365 nm | 700 nm | 0.36 |
| CsPbI$_3$ Film [15] | 365 nm | 700 nm | 0.4 |
| CsPbBr$_3$ Nanowires/PLMA [60] | 456 nm | 517 nm | 0.44 |
| CH$_3$NH$_3$PbI$_3$/PVDF [48] | 405 nm | 521 nm | 0.33 |
| CsPbBr$_3$ Nanorods/PS [49] | 450 nm | 526 nm | 0.23 |
| CsPbBr$_3$ Nanowires/PU [25] | 400 nm | 490 nm | 0.3 |
| CsPbBr$_3$ Nanowire (Single Particle) [56] | 405 nm | 515 nm | 0.78 |
| CH$_3$NH$_3$PbBr$_3$ Nanoplatelets/TPX [16] | 405 nm | 520 nm | 0.11 |
| CH$_3$NH$_3$PbBr$_3$/PVA Nanofibers Film [21] | 405 nm | 522 nm | 0.42 |
| CsPbBr$_3$ Nanowires/block copolymer [61] | 405 nm | 517/660/450 nm | 0.48 for 517 nm |
Zelong Bai received his Ph.D. degree in 2018 from the Beijing Institute of Technology (BIT), Beijing, China. Currently, he is working as a postdoc with Prof. Haizheng Zhong and Prof. Liangyu Zhao in BIT. His project is focus on the research of novel quantum dots composites for photonics and optoelectronics applications.

Haizheng Zhong obtained his B.E. degree in 2003 from Jilin University, and then undertook his Ph.D. studies at the Institute of Chemistry, Chinese Academy of Sciences (ICCAS) with Prof. Yongfang Li from 2003 to 2008. After that, he worked as a postdoc with Prof. Greg Scholes at the University of Toronto during 2008–2010. He joined School of Materials Science & Engineering at Beijing Institute of Technology (BIT) as an associate professor in 2010 and was promoted to full professor in 2013. His current working as a postdoc with Prof. Haizheng Zhong and Prof. Liangyu Zhao in BIT. His current research interests are in the area of colloidal quantum dots for photonics and optoelectronics applications. Since 2019, he serves as senior editor for Journal of Physical Chemistry Letters.

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