# Perovskite as Color Conversion Materials for Micro-LED Displays

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***Abstract*—Metal halide perovskite materials have attracted great attention owing to their fascinating optoelectronic characteristics and low-cost fabrication via facile solution processing. One of the potential applications of these materials is to employ them as color-conversion layers (CCLs) for visible blue light to achieve micro-LED full-color displays. However, obtaining thick perovskite films and fine patterns to realize complete color conversion and vivid display performance is still very challenging. Here, we elaborately addressed above issues and successfully demonstrated efficient blue-to-green photoconversion based on perovskite materials and applied in full color micro-LED displays.**

***Keywords—Micro-LED, Perovskite, Photoconversion, Color conversion***

## I. Introduction

In 2014, Tan et al. demonstrated halide perovskite light-emitting diodes (PeLEDs) operating at room temperature for the first time, which only exhibited external quantum efficiencies (EQEs) of <1%.[1] Since then, research on PeLEDs have attracted tremendous attention and gained rapid developments.[2, 3] Currently, LEDs based on perovskite materials have achieved EQEs of over 20%,[4-8] which are comparable to the records of devices based on organic emitting materials. Nevertheless, further improvements towards stability are yet needed since the lifetime of the reported devices is too short for consumer applications.

Besides the application in LEDs, perovskite materials have also been adopted as downconverters in the backlight for liquid crystal displays (LCDs) .[9-11] In 2016, Zhou et al. demonstrated stable green emissive films composed of $MAPbBr_3$ nanocrystals embedded polymer matrix through an in-situ process.[10] Color gamut of 121% NTSC was achieved by integrating these perovskite polymer composite films and red emissive phosphor with blue InGaN chips. In the same year, Wang et al. realized comparable results through swelling-deswelling microencapsulation strategy.[11] Both of the aforementioned films are proved to be ultrastable even in ambient atmosphere, which manifest considerate possibilities for their future commercialization. In 2018, Chen and co-workers successfully applied perovskite films into an LCD prototype for the first time.[9]

In backlight applications, the photonic energy conversion of short-wavelength light sources is generally incomplete, therefore, incorporation of color filters is inevitable. However, when it comes to the incorporation of suitable materials as color-conversion layers (CCLs) for visible blue light to achieve full color display, complete photoconversion should be enabled. Perovskite materials originally possess the potential to be utilized as CCLs for visible blue light due to their rather high photoluminescence quantum yields (PLQYs) and bright vivid colors.[12-14] However, obtaining thick perovskite films and fine patterns to realize complete color conversion and vivid display performance is still very challenging. Therefore, there is still few demonstrations of perovskite CCLs for displays. Here, we elaborately addressed above issues and successfully demonstrated efficient blue-to-green photoconversion based on perovskite materials and applied in full color micro-LED displays.

## II. Vacuum-Drying Processed Perovskite for Blue-to-Green Photoconversion

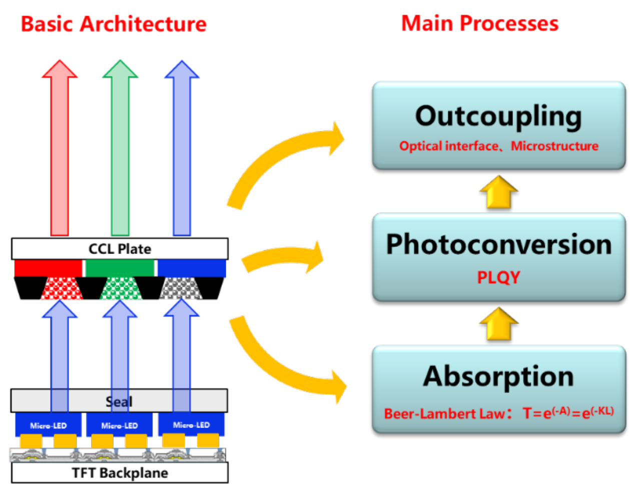


**Figure 1.** Basic architecture of color-converted full-color micro-LED display and the related main photonic processes.

As manifested in Figure 1, there are three main photonic processes involved in color-converted displays, those are: light absorption, photoconversion and outcoupling. Of the three processes, adequate light absorption is the primary condition to ensure complete photoconversion from short-wavelength light sources (such as: blue light). Based on Beer-Lambert Law, the light absorption of a film is proportional to its thickness and coefficient. Therefore, if the perovskite CCL is not thick enough, a portion of back light will remain unconverted thereby resulting in incomplete photoconversion. Currently, spin casting is the most widely adopted method to fabricate perovskite films while it is only suitable for nanometer-thick films which are not adequately thick to be employed as CCLs. Therefore, a key challenge for perovskite materials to apply them as CCLs is to obtain films with higher thickness. Solvent annealing [15, 16] or gas-solid [17] methods have been used

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to fabricate over one micrometer-thick perovskite films, however, they are still not sufficiently thick for efficient photoconversion.

Here, micrometer-thick stable $CsPbBr_3$ perovskite films are obtained through facile vacuum drying (VD) process.[18] As displayed in Figure 2, complete and efficient photo conversion from blue light (@ 463 nm) is successfully demonstrated for the first time. Green emission with a brightness of as high as 200 cd/m² is achieved from blue light with a back luminance of 1000 cd/m² which decayed by only ~2% when the films were tested after 18 days of exposure to ambient environment. To check the actual color conversion performance for further display applications, we took a 3-□m-thick film and stacked it on the top of a micro-LED display and a smartphone display with a blue Peking University (PKU) logo. Noticeably, the blue patterns were efficiently converted to green images.

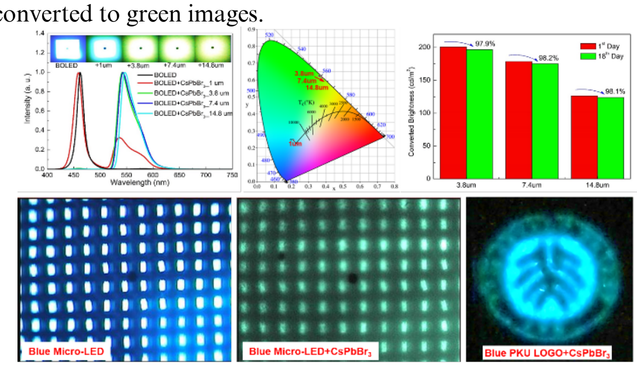


**Figure 2.** Photoconversion performance of $CsPbBr_3$ perovskite films.

## III. Pattering of Perovskite Color Conversion Films

Although efficient green photoconversion films have been demonstrated by the VD method, the displayed images are blurred. In order to incorporate perovskite materials into display panels, precise and uniform patterns are required. After comparing the characteristics of micro-contact printing, photolithography, and IJP methods, the IJP method was chosen to fabricate patterned perovskite films. Combined with the UV curing strategy, uniform micron-level perovskite patterns were successfully fabricated.[19] By this method, the thickness of the film can be precisely controlled by the volume of the ink droplets while eliminating the coffee ring effect.

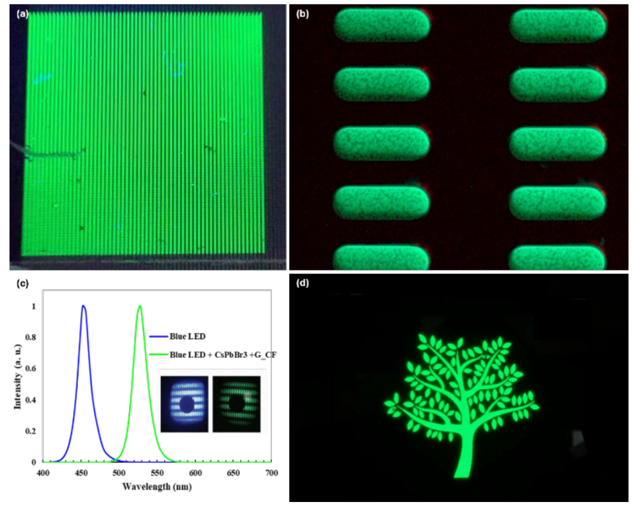


**Figure 3.** Photoconversion performance of green CCLs fabricated through IJP method.

As shown in Figure 3, the photoconversion performance of the fabricated CCLs were further characterized. Under UV light (365 nm) irradiation, the films exhibited good luminescence uniformity both for macroscopic films (as in Figure 3a) and microscopic films within Bank pixels (as in Figure 3b), which indicates that the UV-curing strategy effectively suppresses the coffee ring effect. Meanwhile, we measured the color conversion characteristics of the 6 □m thick film, as shown in Figure 3c, and successfully achieved the blue-green conversion under the excitation of the blue OLED in combination with a green CF. Further we fabricated a 6.6-inch green display combined this CCL plate with a blue OLED backlight display. Apparently, vivid green tree-like images were successfully achieved as shown in Figure 3d.

## IV. CCL Converted Micro-LED Display

Finally, blue backlight and CCL plates were capably assembled to obtain the full-color prototype, as demonstrated in **Figure 4**a-b.[20, 21] Peking University logos in different colors, enabled by this prototype, are displayed in Figure 4c-e which exhibit high color purities. Furthermore, a colorful image of strawberries (Figure 4f) is also well-displayed by our QD CCLs-incorporated micro-LED display. These demonstrations confirm that incorporating $CsPbBr_3$ perovskite and CdSe QD CCLs with bottom-emitting LEDs is an effective strategy to realize effieicnt full-color micro-LED displays. The color gamut of this demo was also calculated, as indicated in Figure 4g, which could reach as high as 97% Broadcasting Service Television 2020 (BT.2020) or 129% NTSC. These color gamut values are much higher than counterpart purely based on RGB micro-LED chips which exhibited 74% BT. 2020 or 99% NTSC (Figure 4g). Furethermore, the color gamut could still reach 94% BT. 2020 or 126% NTSC even when only green light is converted through $CsPbBr_3$ CCL while the other two colors are achived from conventional micro-LEDs. It is worth mentioning that the perovkite CCL utilized here played a vital role in achieving such high color gamuts. Considering these excellent results, it is obvious that incorporating perovskite CCLs with micro-LEDs is a promising approach to realize effieicnt full-color display.

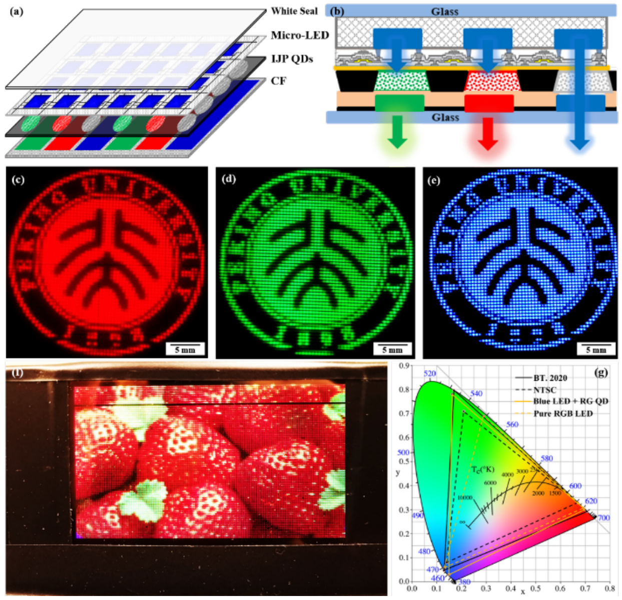


**Figure 4.** Schematic structure and display performance of the fabricated prototype. (a) Schematic illustration and (b) cross-section structure diagram of the prototype. (c) Red, (d) green and (e) blue images of Peking University logo and (f) vivid strawberry image manifested by this CCLs-incorporated Micro-LED display. (g) Color gamut of BT. 2020, NTSC standard, the demonstrated module and conventional Micro-LED display purely based on RGB LED chips.

## V. Summary

In summary, a novel full-color display based on bottom-emitting blue micro-LED backlight with $CsPbBr_3$ perovskite QDs as CCL is demonstrated. By adopting bottom-emitting backlight design, the risk of crosstalk among various pixels is effectively eliminated. In contrast to conventional micro-LED displays purely based on RGB LEDs, this prototype manifests significantly higher color gamut which could reach as high as 129% NTSC or 99% BT. 2020. Notably, the color gamut could still approach 126% NTSC or 94% BT. 2020 even when only green emission is obtained from perovskite CCL while red and blue colors are achieved from conventional micro-LEDs. This full-color display fabrication approach simultaneously harnesses the potential of perovskite materials with high color purity and LEDs with high efficiency and stability. We anticipate that these results would further promote the development of perovskites as CCLs for full-color display applications.

## Acknowledgment

This work is financially supported by the National Natural Science Foundation of China (Grant No. 62205058), the GuangDong Basic and Applied Basic Research Foundation (No. 2021A1515110085), the Shenzhen Fundamental Research Program (No. GXWD20201231165807007-202008101-13811001), the Shenzhen Hong Kong Innovation Circle Joint R&D Project (SGDX20190918105201704), the Development and Reform Commission of Shenzhen Municipality (XMHT20220106002), and the Shenzhen Science and Technology Program (JSGG20220831103402005).

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