Efficient Perovskite Light-Emitting Diodes Enabled by Synergetic Device Architecture

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ABSTRACT

In this work, we demonstrated a facile route was realized by combining bioinspired moth-eye nanostructures and half-ball lens to enhance light outcoupling. As a result, the maximum external quantum efficiency of green perovskite light-emitting diodes was improved to 28.2%, which represented a substantial step toward achieving practical applications of PeLEDs.

1 INTRODUCTION

Perovskite light-emitting diodes (PeLEDs) are gaining considerable attention for applications in next-generation displays and lighting[1-5]. However, EQE in conventional PeLEDs remains severely limited by low light outcoupling efficiency[6]. The majority or 30%-50% of the internally generated light is optically confined or lost in the waveguide modes due to the mismatched refractive indices (n) between the perovskite layer and the glass substrate. To enhance the outcoupling efficiency in conventional inorganic and organic LEDs, numerous methods have been implemented by adopting various photonic structures at the appropriate device interfaces, such as microlens arrays, diffraction gratings, high- or low-refractive-index coupling layers, and so on[7-10].

Here we present a simple and cost-effective method for outcoupling the waveguided light in PeLEDs by embedding a bio-inspired moth-eye nanostructures (MEN) at the front electrode/perovskite interface via soft imprinting technique. As a result, the maximum EQE and current efficiency (CE) of the MEN-modified cesium lead bromide ($CsPbBr_3$) green-emitting PeLEDs are improved to 20.3% and 61.9 cd A^{-1}. Furthermore, by using a half-ball lens to outcouple the light trapped in the substrate mode, we succeeded in increasing the EQE and CE respectively to 28.2% and 88.7 cd A^{-1}, which are the best values ever reported for green- and red-emitting PeLEDs.

2 RESULTS AND DISCUSSIONS

This Figure 1a illustrates the fabrication process of a PeLED with the embedded MEN by adopting a simple nanoimprinting technique. The MEN pattern in the polydimethylsiloxane (PDMS) mold was transferred to the sol-gel-derived zinc oxide (ZnO) layer on ITO glass substrate with a compressive stress. Then, the whole device was completed by depositing PEDOT:PSS, all-inorganic $CsPbBr_3$ perovskite, TPBi, and LiF/Al. Figure 1b-g present the atomic force microscopy (AFM) images of functional layers without and with the MEN pattern. Compared to the smooth surface of a flat ZnO layer (Figure 1b), the quasi-periodic sub-wavelength structures can be observed on the MEN-patterned ZnO layer (Figure 1c). It is worth noting that the MEN pattern can be well duplicated by the subsequently spin-coated PEDOT:PSS layer except for the shallower groove depth. However, the perovskite layers deposited on both flat and patterned PEDOT:PSS substrates exhibit a smooth surface with no apparent difference in morphology (Figure 1f-h).

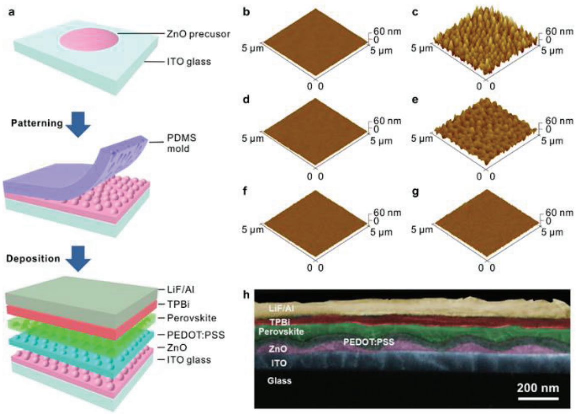

Figure 1. Device fabrication and film morphologies.

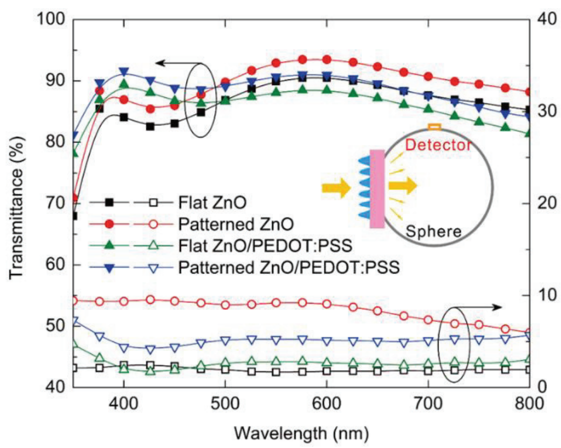

Figure 2. Total transmittance and haze of flat and patterned substrates.

Figure 2 displays that the adoption of the MEN patterns induces a remarkable increase in total transmittance over a wide spectral range of 350-800 nm compared to the flat ZnO or flat ZnO/PEDOT:PSS layer. As shown in Figure 2, the haze values of the patterned substrates are higher than those of the flat ones. An increase in haze represents the stronger light scattering in the patterned ZnO and ZnO/PEDOT:PSS layers, indicating the considerable opportunity for outcoupling enhancement of waveguided light in MEN-patterned PeLEDs.

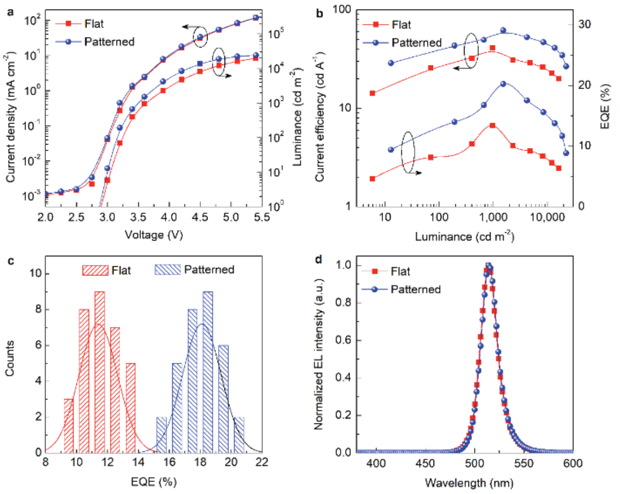

Figure 3. Performance characteristics of the flat and patterned $CsPbBr_3$ PeLEDs.

Table 1. Performance comparison for the flat and patterned $CsPbBr_3$ PeLEDs.

Devices	V_{on} [V]	EL [nm]	EQE [%]	CE [cd A^{-1}]
Flat	2.84	514	13.4	40.9
Patterned	2.76	514	20.3	61.9
Patterned+Lens	2.74	514	28.2	88.7

Figure 3 and table 1 compare the performance characteristics of the flat and patterned PeLEDs. As plotted in Figure 3a-b, the device efficiency of the patterned PeLED is significantly enhanced compared to that of the flat one while the flat and MEN-patterned devices exhibit almost identical current density-voltage (J-V) characteristics. The maximum EQE and CE values of the patterned PeLED reach to 20.3% and 61.9 cd A^{-1} respectively. The EQE histograms in Figure 3c show the high reproducibility of both the patterned and flat $CsPbBr_3$ PeLEDs. Figure 3d compares the normalized EL spectra in the forward direction for the flat and patterned devices, showing the identical green emission centered at 514 nm with a narrow full-width at half-maximum (FWHM) of 18 nm. To extract the light trapped in the substrate mode, a half-ball lens was mounted on top of the glass substrate with an index matching gel. As shown in Table 1, the maximum EQE and CE of the PeLEDs are further improved to 28.2% and 88.7 cd A^{-1}.

Figure 4 displays the simulated cross-section views of the near-field intensities of the transverse electric (TE) polarized light in the flat and patterned PeLEDs simulated via the finite-difference-time-domain (FDTD) method. Compared to the flat device structure, some amount of the internally confined light will be effectively outcoupled into the glass substrate due to the presence of the MEN pattern, which are in agreement with our experimental observations.

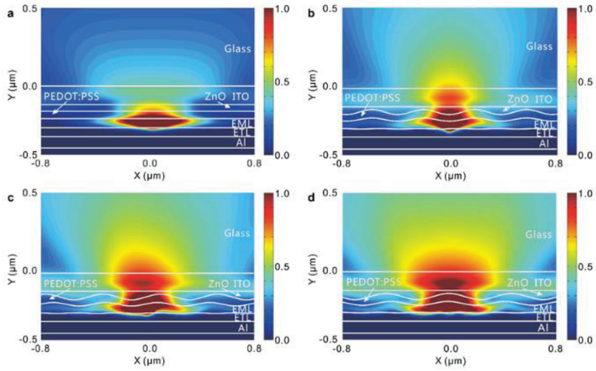

Figure 4. Simulation of light outcoupling in PeLEDs

3 CONCLUSIONS

High-performance $CsPbBr_3$ PeLEDs have been achieved by implementing simple and cost-effective methods for efficient outcoupling of waveguided light. By embedding a MEN-based outcoupling structure at the front electrode/perovskite interface, a large amount of the trapped light is guided to scatter out. Furthermore, additional outcoupling of the light trapped in the substrate mode is induced by using a half-ball lens. As a result, a record EQE of 28.2% is achieved for PeLEDs, which represents a substantial step toward achieving practical applications of PeLEDs.

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REFERENCES

[1] Z.-K. Tan, R. S. Moghaddam, M. L. Lai, P. Docampo, R. Higler, F. Deschler, M. Price, A. Sadhanala, L. M. Pazos, D. Credgington, F. Hanusch, T. Bein, H. J. Snaith, R. H. Friend, Bright Light-Emitting Diodes Based on Organometal Halide Perovskite. *Nat. Nanotechnol.* **2014**, *9*, 687-692.

[2] H. Cho, S.-H. Jeong, M.-H. Park, Y.-H. Kim, C. Wolf, C.-L. Lee, J. H. Heo, A. Sadhanala, N. Myoung, S.

Yoo, S. H. Im, R. H. Friend, T.-W. Lee, Overcoming the Electroluminescence Efficiency Limitations of Perovskite Light-Emitting Diodes. *Science* **2015**, *350*, 1222-1225.
[3] Y. Ling, Z. Yuan, Y. Tian, X. Wang, J. C. Wang, Y. Xin, K. Hanson, B. Ma, H. Gao, Bright Light-Emitting Diodes Based on Organometal Halide Perovskite Nanoplatelets. *Adv. Mater.* **2016**, *28*, 305-311.
[4] N. Wang, L. Cheng, R. Ge, S. Zhang, Y. Miao, W. Zou, C. Yi, Y. Sun, Y. Cao, R. Yang, Y. Wei, Q. Guo, Y. Ke, M. Yu1 Y. Jin, Y. Liu, Q. Ding, D. Di, L. Yang, G. Xing, H. Tian, C. Jin, F. Gao, R. H. Friend, J. Wang, W. Huang, Perovskite Light-Emitting Diodes Based on Solution-Processed Selforganized Multiple Quantum Wells. *Nat. Photon.* **2016**, *10*, 699-704.
[5] M. Yuan, L. N. Quan, R. Comin, G. Walters, R. Sabatini, O. Voznyy, S. Hoogland, Y. Zhao, E. M. Beauregard, P. Kanjanaboos, Z. Lu, D. H. Kim, E. H. Sargent, Perovskite Energy Funnels for Efficient Light-Emitting Diodes. *Nat. Nanotechnol*. **2016**, *11*, 872-877.
[6] S. S. Meng, Y. Q. Li, J. X. Tang, Theoretical Perspective to Light Outcoupling and Management in Perovskite Light-Emitting Diodes, *Org. Electron*. **2018**, *61*, 351-358.
[7] J. P. Yang, Q. Y. Bao, Z. Q. Xu, Y. Q. Li, J. X. Tang, S. Shen, Light out-coupling enhancement of organic light-emitting devices with microlens array, *Appl. Phys. Lett.* **2010**, *97*, 223303.
[8] S. Reineke, F. Lindner, G. Schwartz, N. Seidler, K. Walzer, B. Lussem, K. Leo, White Organic Light-Emitting Diodes with Fluorescent Tube Efficiency. *Nature* **2009**, *459*, 234-238.
[9] Z. B. Wang, M. G. Helander, J. Qiu, D. P. Puzzo, M. T. Greiner, Z. M. Hudson, S. Wang, Z. W. Liu, Z. H. Lu, Unlocking the Full Potential of Organic Light-Emitting Diodes on Flexible Plastic. *Nat. Photon.* **2011**, *5*, 753-757.
[10] Y. Sun, S. R. Forrest, Enhanced Light Out-Coupling of Organic Light-Emitting Devices Using Embedded Low-Index Grids. *Nat. Photon*. **2008**, *2*, 483-487.