Improvement of perovskite photoluminescence characteristics by using a lithography-free metasurface

Wenjun Chen[1], Jun Sha[1], Kanghong Yan[1], Ji Luo[1], Ruijia Xu[1], Dongyuan Yao[1], Xiaoyan Liu[1], Shaoquan Liao[1], Jitong Zhong[1], Shengrong Yang[1], Yangbin Yu[1], Yanlin Tong[1], Zefeng Xu[1], Yu-Sheng Lin[1]*, and Tsung-Sheng Kao[2]*
[1]State Key Laboratory of Optoelectronic Materials and Technologies,
School of Electronics and Information Technology, Sun Yat-Sen University, Guangzhou 510275, China
[2]Department of Photonics, National Chiao Tung University, Hsinchu 300, Taiwan.
E-mail: linyoush@mail.sysu.edu.cn and tskao@nctu.edu.tw

***Abstract*—Organic-inorganic metal halid perovskite is an emerging field of promising semiconductive material in optoelectronic devices applications. It has been a research topic of interest for scientists. To date, photoluminescence (PL) efficiency of perovskite is low and does not have any literature to report the solution. Here, we proposed and demonstrated an effective approach for the improvement of perovskite PL characteristics. The PL intensity and spectra bandwidth could be enhanced significantly by using Al-disk metasurface formed on perovskite surface. Such strategy can be exploited to enhance perovskite PL characteristics for developing high efficient light emitting diodes, solar cells, and photodetectors, etc.**

Keywords—perovskite, photoluminescence, metasurface, lithography-free

I. INTRODUCTION

Recently, organic-inorganic metal halid perovskite is promising candidate for light emitting diodes (LEDs), photodetector, lasers, photovoltaics and solar cells [1-4], owing to its optoelectronic properties, such as strong optical absorption, high carrier mobility, ambipolar charge-transport characteristics and tunability of bandgap and so on [5, 6]. Such optoelectronic properties make perovskite be an excellent candidate for the development of optoelectronic device. One of optoelectronic properties of perovskite is PL characteristic, which is directly to impact the optical performance of optoelectronic devices. The improvement of perovskite PL characteristic for solar cells and photodectors applications has been extensively investigated during the last few years. However, the improvement of PL property is limit. Therefore, to enhance perovskite PL characteristics is still a challenge.

In this study, we report an effective approach to enhance perovskite PL intensity and narrow PL spectra bandwidth by using a lithography-free metasurface. The metasurface is composed of Al-disk structures fabricated by using direct metal deposition and post thermal annealing treatment on perovskite surface. We systematically investigated PL enhancement of perovskite before and after thermal annealing treatment. We demonstrate a strong modification of perovskite optical emission properties, which is useful for studying perovskite-based optoelectronic devices with a low-cost and high efficiency, such as LEDs and lasers, etc.

II. METHODS

Fig. 1(a) shows the fabrication process of perovskite with Al-disk metasurface atop. First, a modified solvent-engineering method was used for methylammonium lead iodide ($MAPbBr_3$) perovskite thin-film deposition. Second, an Al thin-film with 70 nm in thickness was deposited on the perovskite surface by using electro-beam evaporation. Third, sample was annealed at 500°C at 1×10^3 Pa for 20 min to form Al-disk on sample surface. The structural morphology of Al-disk metasurface was characterized by using scanning electron microscopy (SEM). The top view of SEM images of Al-disk metasurface on perovskite surface before and after thermal annealing treatment are shown in Fig. 1(b) and (c), respectively. In Fig. 1(b), the morphology of Al thin-film deposited on perovskite surface is non-uniform owing to the perovskite surface was coated by using solvent-engineering method. After thermal annealing treatment, it reveals that the perovskite surface covered a random and uniform Al-disk metasurface with a grain size in the range of 0.5 μm to 1 μm as show in Fig. 1(c).

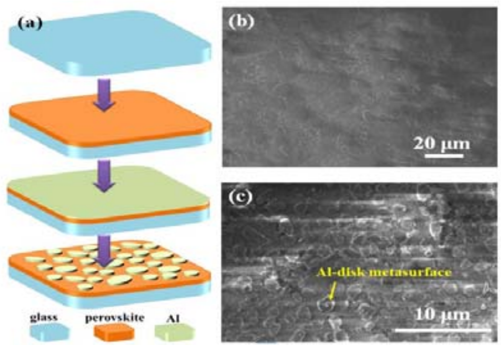

Fig. 1. (a) Fabrication process of the proposed device and top-view SEM images of Al-disk metasurface on perovskite surface (a) before and (b) after thermal annealing treatment.

III. RESULTS AND DISCUSSIONS

Fig. 2 implies that a number of electrons transfer from Al-disk metasurface to perovskite material. Therefore, the Al-disk metasurface acts as n-type dopants in perovskite. For convenience to mention afterward, the samples are bare perovskite thin-film, perovskite covered with an Al thin-film and perovskite covered with Al-disk metasurface are denoted as S1, S2, and S3, respectively. The optical emission properties of three samples are characterized by using PL equipped with a laser (model: OBIS 405) and a commercial spectrometer (model: ANDOR Newton 970). Fig. 3 shows the schematic drawing of PL measurement setup for three samples. The room-temperature PL measurement results of three samples are presented in Fig. 4. The excitation power for PL measurement is 5 mW and the exposure time is 0.999 seconds. The perovskite thin-film without Al metal thin-film, i.e. (S1 sample) shows a PL peak wavelength of PL at 540 nm with a full width at half maximum (FWHM) of 23 nm, while S2 shows a peak wavelength of PL at 530 nm with a FWHM of 25 nm and S3 shows a peak wavelength of PL at 530 nm with a FWHM of 20 nm. PL intensity properties of three samples were also measured. The PL intensity of S3 was enhanced 4.2-fold to compare to S1, which is attributed to Al-disk metasurface to generate near-field plasmonic resonance between Al-disk structures. To further improve PL performance of perovskite, we prepared another sample (S4) with nanocomposites fabricated on perovskite surface. The nanocomposites are composed of Al/perovskite nanopillars. The schematic drawing is shown in the inserted image of Fig. 5. Fig. 5 shows the peak wavelength of PL at 525 nm with a FWHM of 2 nm, which has improved significantly compared to S1, S2, and S3. Meanwhile, the PL intensity was improved 5.2-fold compared to that of S1.

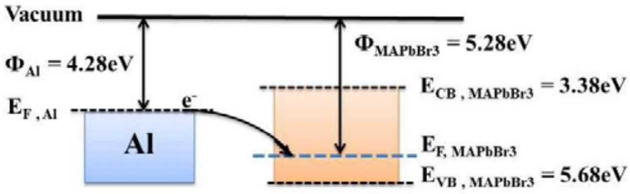

Fig. 2. The schematic energy band diagram for $MAPbBr_3$ and Al.

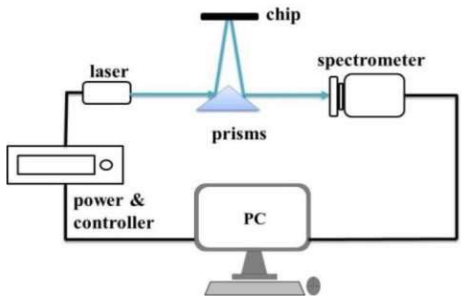

Fig. 3. Schematic drawing of PL measurement setup.

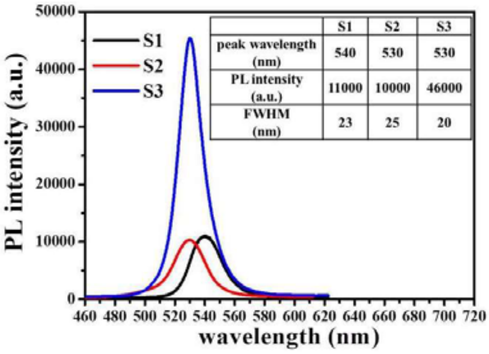

Fig. 4. The measurement results of PL intensity of S1 (black line), S2 (red line) and S3 (blue line).

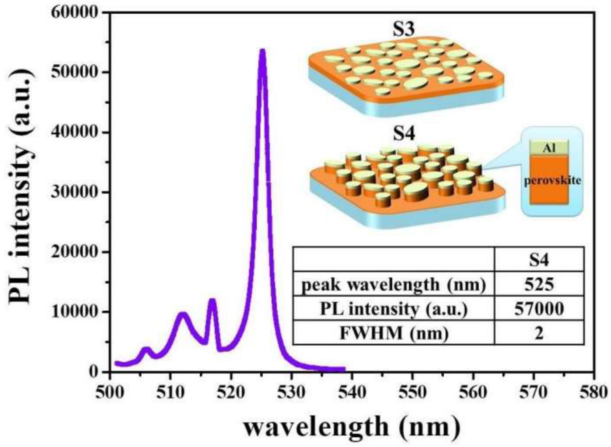

Fig. 5. The measurement result of PL intensity of S4

IV. Conclusion

In conclusion, we proposed an effective approach to improve PL characterizes of organic-inorganic halide perovskite, which surface is distributed Al-disk structures randomly and uniformly by using direct metal deposition and post thermal annealing treatment. The perovskite PL intensities of S3 and S4 were enhanced 4.2-fold and 5.2-fold compared to that of S1, while the spectra bandwidths of S3 and S4 were narrower 13% and 91% than that of S1, respectively. This cost-effective method with high applicability, and cost-effectiveness using Al-disk metasurface could be widespread used in solar cells, LEDs, lasers, photodetectors and other fields. Such stable optical performance permits perovskite with Al-disk metasurfce to realize high efficient optoelectronic devices and provides a greater possibility for industrial use.

Acknowledgment

The authors acknowledge the financial support from research grants of 100 Talents Program of Sun Yat-Sen University (grant number 76120-18831103) and the State Key Laboratory of Optoelectronic Materials and Technologies of Sun Yat-Sen University for the use of experimental equipment.

References

[1] 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, and E. H. Sargent, "Perovskite energy funnels for efficient light-emitting diodes," Nat. Nanotechnol. 11(10), 872–877 (2016).

[2] X. Hu, X. Zhang, L. Liang, J. Bao, S. Li, W. Yang, and Y. Xie, "High-performance flexible broadband photodetector based on organolead halide perovskite," Adv. Funct. Mater. 24, 7373–7380 (2014).

[3] G. Xing, N. Mathews, S. S. Lim, N. Yantara, X. Liu, D. Sabba, M. Grätzel, S. Mhaisalkar, and T. C. Sum, "Low-temperature solution-processed wavelength-tunable perovskites for lasing," Nat. Mater. 13(5), 476–480 (2014).

[4] M. M. Lee, J. Teuscher, T. Miyasaka, T. N. Murakami, H. J. Snaith,Science 2012, 338, 643;

[5] M. A. Green, A. Ho-Baillie, and H. J. Snaith, "The emergence of perovskite solar cells," Nat. Photonics 8, 506–514 (2014).

[6] C. Wehrenfennig, G. E. Eperon, M. B. Johnston, H. J. Snaith, and L. M. Herz, "High charge carrier mobilities and lifetimes in organolead trihalide perovskites," Adv. Mater. 26(10), 1584–1589 (2014).