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Monte-Carlo simulations of optical efficiency in luminescent solar concentrators based on all-inorganic perovskite quantum dots

Junpeng Shu[a], Xiaowei Zhang[a,b,*], Pengjun Wang[a,c,**], Ruowang Chen[a], Huihong Zhang[a], Dongke Li[b,d], Pei Zhang[b,e], Jun Xu[b]

[a] Faculty of Electrical Engineering and Computer Science, Ningbo University, Ningbo, 315211, China
[b] National Laboratory of Solid State Microstructures, Department of Electronic Science and Engineering, Nanjing University, Nanjing, 210093, China
[c] College of Mathematical, Physics and Electronic Information Engineering, Wenzhou University, Wenzhou, 325035, China
[d] Physics Department and Jiangsu Key Laboratory for Chemistry of Low-Dimensional Materials, Huaiyin Normal University, Huaian, 223300, China
[e] Materials and Nano Physics Department, ICT School, KTH Royal Institute of Technology, Kista, 16440, Sweden

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ABSTRACT

Luminescent solar concentrator (LSC) devices emerge as a promising technology to reduce the cost of electricity generated by photovoltaic solar cells. Here, we demonstrate the detailed fabrication process of non-crystalline LSC prototype devices based on all-inorganic perovskite quantum dots (QDs) for the first time. The as-prepared all-inorganic perovskite QDs show many advantages, such as tunable absorption spectrum over the entire visible spectral region, high photoluminescence (PL) quantum yield (QY) up to 50%, and narrow emission line widths with FWHM (full width at half maximum) of 17–26 nm, which may greatly improve the optical efficiency of LSC prototype devices. On the optimal doping concentrations, Monte Carlo ray-tracing simulations indicate the LSC prototype devices have an extremely high average optical efficiency, which is 1.22% for $CsPbCl_3$ QDs, 5.43% for $CsPbBr_3$ QDs, and 7.39% for $CsPbI_3$ QDs, respectively. We anticipate these potential high-efficiency LSC prototype devices based on perovskite QDs will shed light on future research of large-scale and high-performance LSCs applications.

1. Introduction

The efficiency of photovoltaic power can be greatly improved by using the solar concentrators. Conventional solar concentrators track the sun with high precision by use of the large mobile mirrors, which are often complicated and expensive. To further reduce the capital and maintenance costs of conventional solar concentrators, forty years ago, the concept of luminescent solar concentrator (LSC) device was first proposed as an alternative, non-tracking approach for low-cost and large-scale photons collection [1]. Typically, an LSC device consists of a non-crystalline optical waveguide doped with highly emissive fluorophores [2,3]. Upon the sunlight penetrates the top surface of the optical waveguide of LSC prototype devices, these fluorophores inside the optical waveguide absorb the sunlight and then re-emit photons at a lower energy by a down-conversion or down-shift process. Unlike other types of solar concentrators, which can only concentrate the direct light, LSC devices can also absorb and concentrate the diffuse light. Due to the total internal reflection of non-crystalline host, these re-emitted photons will be trapped inside the optical waveguide and concentrated on the edge of the LSC device. The core part of the LSC device is the fluorophores. Since 1970s, a variety of fluorophores inside LSC devices have been extensively investigated to achieve high-efficiency optical efficiency. At the early stage of LSC device designs, organic dyes, such as Coumarin and Rhodamine, always are demonstrated as the high-performance emissive fluorophores of LSC devices because of their good solubility, large absorption coefficients, and high photoluminescence (PL) quantum yield (QY) [4]. However, the inevitable disadvantages of organic dyes as fluorophores, such as the limited absorption spectra and unfriendly photo-degradation effect, still severely hinder the advancement of large-scale applications of LSC devices based on organic dyes. Recently, various kinds of inorganic-based quantum dots (QDs), such as PbS QDs [5], CdSe/CdS QDs [6], Si QDs [7], InP QDs [8], CuInSeS QDs [9], are reported as the promising emissive fluorophores for future applications of LSC devices. On the one hand, the absorption cross-sections and emission of inorganic-based QDs can be tuned by the average size via the quantum confinement effect. On the other hand,

* Corresponding author. Faculty of Electrical Engineering and Computer Science, Ningbo University, Ningbo, 315211, China.
** Corresponding author. Faculty of Electrical Engineering and Computer Science, Ningbo University, Ningbo, 315211, China.
E-mail addresses: zhangxiaowei@nbu.edu.cn (X. Zhang), wangpengjun@nbu.edu.cn (P. Wang).

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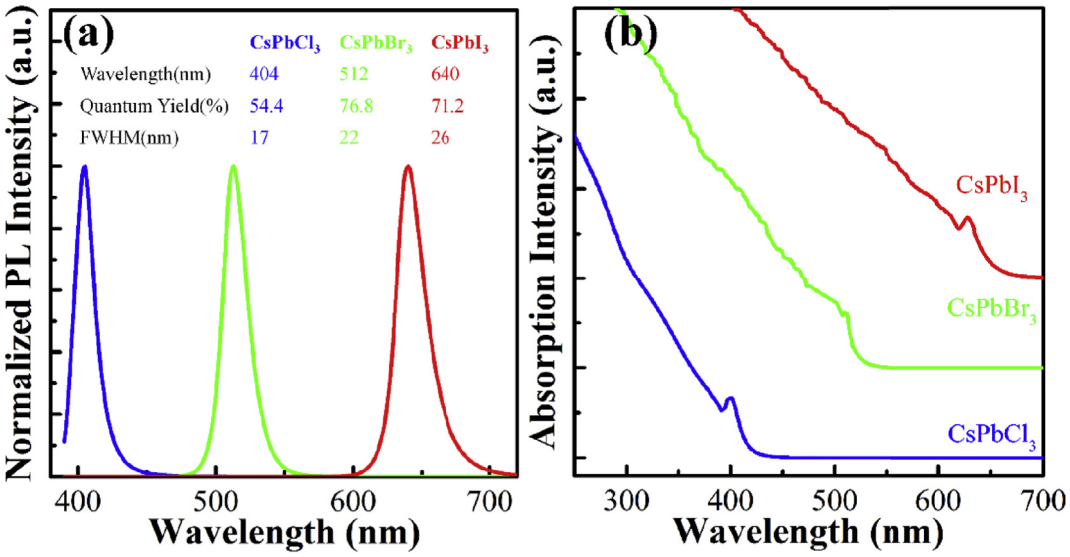

Fig. 1. (a) PL and (b) absorption spectra of the all-inorganic perovskite QDs.

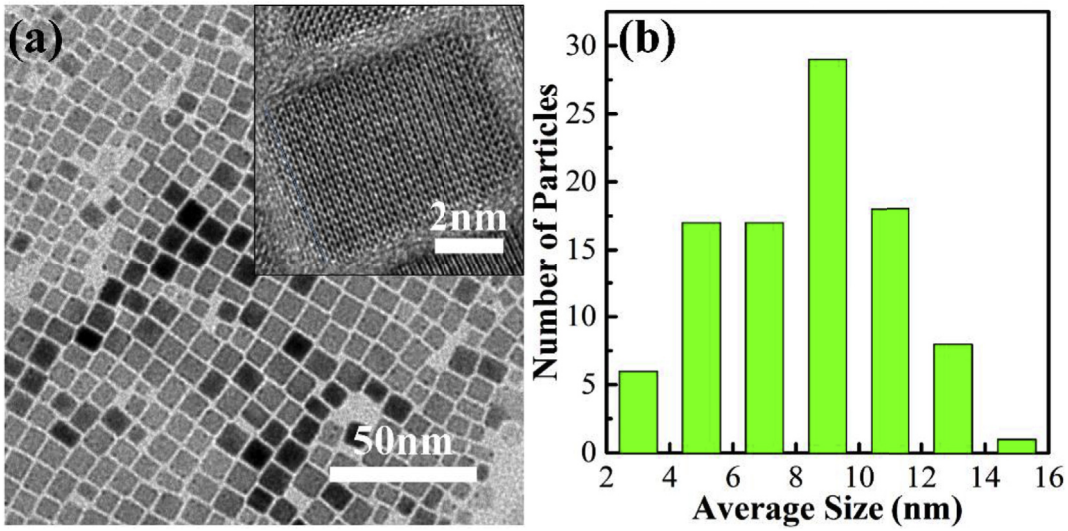

Fig. 2. (a) Low-resolution TEM image of typical colloidal perovskite QDs. Inset is the related high-resolution TEM image. (b) The size distribution histogram of colloidal perovskite QDs.

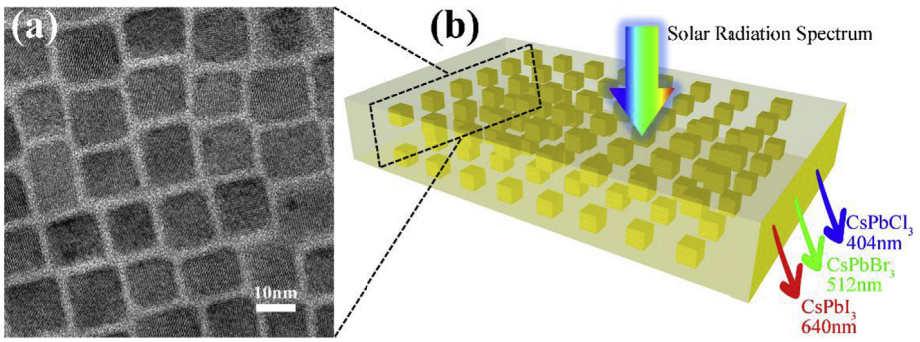

Fig. 3. (a) TEM image of typical colloidal perovskite QDs. (b) Scheme of a LSC prototype device based on all-inorganic perovskite QDs.

the photo-stability of inorganic-based QDs over organic dyes is greatly improved due to the robust crystalline structure. Here, the detailed fabrication processes of all-inorganic $CsPbX_3$ (X = Cl, Br, I) perovskite QDs merged into non-crystalline poly (allyl monomers-co-thiol monomers) polymer matrix have been demonstrated for the first time as the novel LSC prototype devices. For all-inorganic perovskite QDs, the following four considerable characteristics will greatly benefit the performance of LSC devices, (1) size/composition dependent bandgap engineering due to larger Bohr diameter up to 12 nm, (2) high PL QY reaching 50%, (3) good photo-stability over hybrid organic-inorganic ones, and (4) wide absorption spectrum and narrow emission line widths. In additions, theoretical simulation is an important method to