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## ACCEPTED MANUSCRIPT

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#### Gas-assisted coating of Bi-based (CH<sub>3</sub>NH<sub>3</sub>)<sub>3</sub>Bi<sub>2</sub>I<sub>9</sub> active layer in perovskite solar cells

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#### **Abstract**

Methylammonium bismuth iodide,  $(CH_3NH_3)_3Bi_2I_9$ , is a promising lead-free perovskite active layer for solar cells. In this study, by using gas-assisted deposition method, we have successfully prepared dense and smooth  $(CH_3NH_3)_3Bi_2I_9$  active layer, resulting in 25% improvement in  $V_{OC}$  (from 0.548 V to 0.686 V) and 17% improvement in efficiency (from 0.070% to 0.082%), compared with the conventional 1-step method.

Keywords: Perovskite solar cells; Lead-free; Bi-based; (CH<sub>3</sub>NH<sub>3</sub>)<sub>3</sub>Bi<sub>2</sub>I<sub>9</sub>; Gas-assisted

#### 1. Introduction

Perovskite solar cells (PSCs) have attracted much attention due to their rapidly-increased and high power conversion efficiency (PCE). Kojima et al. reported the PSCs with conversion efficiency of 3.8 % in 2009 [1]. Within only 7 years, the PCE increased up to 22.1% [2]. The high efficiency is attributed to excellent optical and electrical properties of CH<sub>3</sub>NH<sub>3</sub>PbX<sub>3</sub> (X=I, Br or Cl) [3-5]. However, the CH<sub>3</sub>NH<sub>3</sub>PbI<sub>3</sub> active layer includes toxic Pb; an alternative lead-free active layer is desired. Sn replacement for Pb has been tried to solve this problem [6,7], but durability is the most serious problem in Sn-based PSCs.

Currently, Bi-based perovskite-type compounds gather much attention [8-14]. Among them, (CH<sub>3</sub>NH<sub>3</sub>)<sub>3</sub>Bi<sub>2</sub>I<sub>9</sub> has high stability in air since Bi<sup>3+</sup> ions are stable, but the typical PCE of (CH<sub>3</sub>NH<sub>3</sub>)<sub>3</sub>Bi<sub>2</sub>I<sub>9</sub> PSCs are reported as 0.1-0.2%. Singh et al. have recently reported the 10-week long-term stability of (CH<sub>3</sub>NH<sub>3</sub>)<sub>3</sub>Bi<sub>2</sub>I<sub>9</sub> PSCs [10], where the performance degradation was only 25% even in the ambient conditions. This result has demonstrated the high stability of (CH<sub>3</sub>NH<sub>3</sub>)<sub>3</sub>Bi<sub>2</sub>I<sub>9</sub> PSCs. Compared with commonly used perovskites having favorable band gaps, *e.g.* CH<sub>3</sub>NH<sub>3</sub>SnI<sub>3</sub> (~1.3 eV [6]) and CH<sub>3</sub>NH<sub>3</sub>PbI<sub>3</sub> (~1.5 eV [15]), (CH<sub>3</sub>NH<sub>3</sub>)<sub>3</sub>Bi<sub>2</sub>I<sub>9</sub> has a wider band gap (~2.1 eV [8,13]). (CH<sub>3</sub>NH<sub>3</sub>)<sub>3</sub>Bi<sub>2</sub>I<sub>9</sub>, however, can be an alternative for CH<sub>3</sub>NH<sub>3</sub>PbI<sub>3</sub> due to the high absorption coefficient ((CH<sub>3</sub>NH<sub>3</sub>)<sub>3</sub>Bi<sub>2</sub>I<sub>9</sub>: 1.1×10<sup>5</sup> cm<sup>-1</sup> at 500 nm [13], CH<sub>3</sub>NH<sub>3</sub>PbI<sub>3</sub>:

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