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Exploring the interfacial effects at the ETL/perovskite boundary in the semitransparent perovskite solar cells

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ABSTRACT

The recent focus has been made on the perovskite solar cells (PSCs) with an inverted configuration, where substantial improvements have been already achieved. However, the *p–i–n* structure needs a buffer layer for most of the configurations to modify the work-function of a deposited electrode. Additionally and very importantly, such a layer can also serve as a protective film that improves a stability of solar cells. Here, we study the semitransparent inverted PSCs, which have been prepared with the SnO_2 buffer layer deposited by a spin-coating method. The main goal was to understand the dominant loss mechanisms in the operation of PSCs. Four photovoltaic parameters (an open-circuit voltage, a short-circuit current, a fill factor and a power conversion efficiency) were measured for a wide range of the light intensity. Their analysis allowed us to identify the transportation and recombination effects using an electrical modeling based on the drift–diffusion model. In addition, it has been concluded that the solution processed PCBM layer might not fully cover the perovskite film. As a consequence, the band-bending effect can occur at the PCBM/perovskite interface, where PCBM plays a role of the Electron Transport Layer (ETL). Therefore, we theoretically investigated the influence of this interface phenomenon on four photovoltaic parameters and the ideality factor simulated as a function of the ETL interface defect density. The increasing of the ideality factor to a high value (above 4) observed for the band-bending level around 300 eV indicates inhomogeneity of the interface. The results of this study should help to better understand the dominant electrical losses in the semitransparent inverted PSCs with a buffer layer which should further help to improve the performance of such devices.

1. Introduction

World energy consumption still increases and it leads to the development of different types of energy sources. Photovoltaics seems to be a very promising form of a renewable energy. Still, solar cells based on crystalline silicon (c–Si) or amorphous silicon (a–Si) are very popular for the conversion of a sunlight into electricity [1]. However, other semiconductors such as gallium arsenide (GaAs) [2] or cadmium telluride (CdTe) [3] can be also used to produce efficient photovoltaic devices. The other effective compound is $CuIn_xGa_{1-x}Se_2$ (CIGS) [4], where cadmium sulfide (CdS) often plays a role of the buffer layer [5,6].

Although photovoltaic panels based on these materials are already used in a daily life, there is a need to find more efficient or cheaper compounds to fabricate solar cells. The class of high absorbing semiconductors Cu_2XSnS_4 (X = Fe, Co, Ni, Cu, Zn, Mn) seems to become an alternative to the CIGS system [7–10]. In addition, researchers try to find optical transparent materials to use them in semitransparent solar cells. Good candidates are Sb_2S_3 and Sb_2Se_3 characterized by a wide band gap [11,12]. In recent decades, photovoltaic devices with organic materials (like donor–acceptor structures [13] and hybrid dye-sensitized solar cells [14]) have attracted a lot of attention. The reason is a low manufacturing cost and possibility to obtain flexible solar cells.

The other type of promising photovoltaic devices are perovskite solar cells (PSCs). Here, we can distinguish hybrid organic–inorganic PSCs [15–17]. They are recently getting attention due to the outstanding increase in power conversion efficiency (PCE), which is already reaching over 20% [18]. It is believed that lead halide PSCs will deliver a very low cost of solar energy (<32 $ per MWh) [19]. In addition, efficient semitransparent PSCs have been fabricated using hybrid organic–inorganic perovskites [20–22], which increases their attractiveness. However, we also observe intensive studies of all-inorganic PSCs [23–27].

At the beginning of the PSCs development, the *n–i–p* (regular planar) stack has been more often used due to achieving higher efficiencies [28]. Here, *n* is the n-type semiconductor and represents an

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