Efficiency improvement of 2T all perovskite tandem solar cell using the SiO_2 nanosphere arrays as an antireflection layer

Mahsa Moradbeigi
Dept. of Physics
Faculty of Science, University of Kurdistan
Sanandaj, Iran
m.moradbeigi@uok.ac.ir

Mohammad Razaghi
Dept. of Electronics and Communication Engineering
Faculty of Engineering, University of Kurdistan
Sanandaj, Iran
m.razaghi@uok.ac.ir

***Abstract*—In this study, an efficient lead-free 2-terminal (2T) all perovskite tandem solar cell (AP-TSC) is proposed. Under the current matching condition, the matched short circuit current density (J_{sc}) and power conversion efficiency (PCE) of the reference structure are obtained as $12.32mAcm^{-2}$ and 29.04%, respectively. Then, SiO_2 nanosphere arrays are placed to the structure's top. By acting as an antireflection layer (ARL), this low-refractive index (RI) layer enhances the J_{sc} and PCE parameters. To achieve maximum $J_{sc} = 14.07mAcm^{-2}$, the optimum diameter (D) and center-to-center distance (W) of the nanoparticles are determined to be 90 nm and 200 nm, respectively. In order to establish the current matching condition, the thickness of the absorber layers in the top and bottom sub-cells (t_{WBG} and t_{NBG}) is calculated to be 200 nm and 224 nm, respectively. Therefore, the final structure with SiO_2 nanoparticle arrays as ARL and a PCE improvement of 14.22%, which reached 30.17%, is presented as a lead-free 2T AP-TSC.**

***Index Terms*—all perovskite, tandem, solar cell, antireflection, nanosphere.**

I. Introduction

Because of eco-friendly feature, its cheap manufacturing costs, and the capacity to surpass the Shockley–Queisser theoretical power conversion efficiency (PCE) limit, lead-free 2-terminal (2T) all perovskite tandem solar cells (AP-TSCs) have attracted a lot of interest [1], [2]. According to reports, SiO_2 nanoparticles can serve as an anti-reflection layer (ARL) [3]. In solar cells, this ARL structure with low-refractive index (RI), forward light scattering, and longer optical paths results in higher J_{sc} and PCE [3]. Here, a 2T AP-TSCs with SiO_2 nanoparticle arrays as ARL is modeled to improve the PCE for the first time.

II. Theory and Modeling

We employed 3D finite element method (FEM) to obtain the opto-electrical parameters in the proposed 2T AP-TSC. Two structures are modeled, which are depicted in Fig. 1. The Structure *I* as reference solar cell is made up of fluorine doped tin oxide (FTO), hydrogen doped indium oxide (IOH) and Au as transparent conductive oxide (TCO), interconnecting layer (IC) and back contact materials, respectively, Spiro-OMeTAD as top and bottom sub-cell's hole transport material, TiO_2 and TiO_2/Gr nanocomposite as electron transport materials of top an bottom sub-cells, respectively, and molybdenum oxide (MoO_x) as buffer layer, as well as $MAGeI_3$ as lead-free wide band-gap (WBG) and $MASnI_3$ as lead-free narrow band-gap (NBG) absorber materials, respectively. Structure *II* is created by adding SiO_2 nanosphere arrays as ARL to top of solar cell.

The Helmholtz equation ($\nabla \times (\nabla \times \mathbf{E}) - k_0^2(n(\lambda) - ik(\lambda))^2\mathbf{E} = 0$) will be solved with perfectly matched layer (PML) and Floquet periodicity boundary conditions in the z- and xy- directions. Therefore, the field distribution as a function of wavelength ($E(\lambda)$) is obtained after entering the real and imaginary components of the RI, are denoted by n, k. where the wave vector is identified k_0. With the following formula, the total photogeneration rate was calculated:

$$G_{tot}(x, y, z) = \int_{300}^{1050} \pi\epsilon'' E^2(x, y, z, \lambda)/h \ d\lambda \qquad (1)$$

Also, the reflection parameter is determined using the S parameters [2].

The photovoltaic parameters include open-circuit voltage (V_{oc}), short circuit current density (J_{sc}), fill factor (FF), and PCE, which are obtained from the current density-voltage (J-V) characteristic curve by solving the Poisson, Continuity, and Drift-diffusion equations. J_{sc} is obtained in the current matching condition, whereas the summation of the open-circuit voltages of the two sub-cells is V_{oc}. The current matching condition is met if the difference between the two sub-cells' J_{sc} reaches zero. The FF and PCE are defined as:

$$PCE = (FF\, J_{sc}\, V_{oc})/P_{in}; FF = (V_{mp}\, J_{mp})/(V_{oc}\, J_{sc}) \quad (2)$$

The voltage and current densities at the maximal power point are indicated by the symbols V_{mp} and J_{mp}, respectively. P_{in} is incident solar spectrum power. Every material's optical and electrical characteristics and details of the simulation are taken from [2].

III. RESULTS AND DISCUSSION

The J-V characteristic curve of structure I is depicted in Fig. 2. Taking into consideration

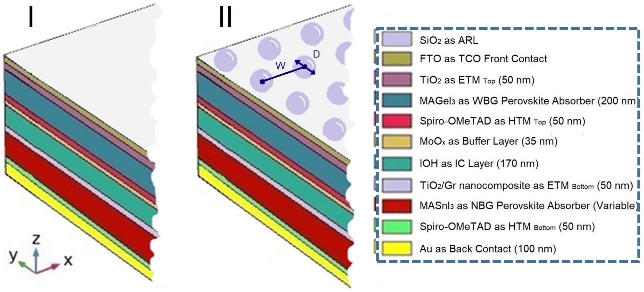

Fig. 1. A 3D schematic of the structures *I* and *II*.

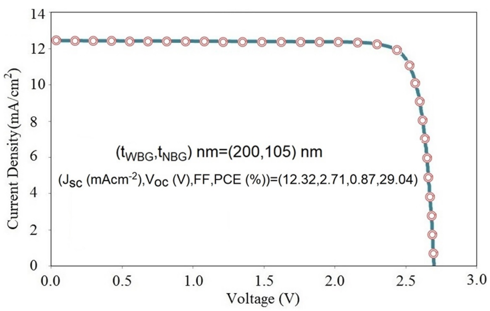

Fig. 2. The J-V characteristics of the structure *I* as reference structure.

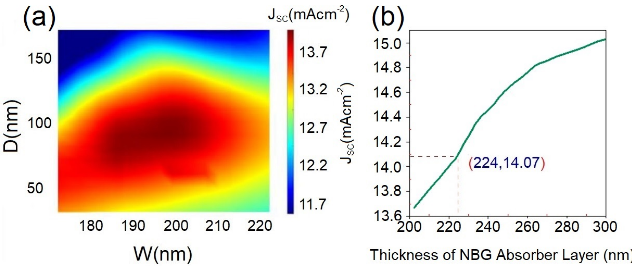

Fig. 3. J_{sc} as a function of a) D and W, and b) t_{NBG}.

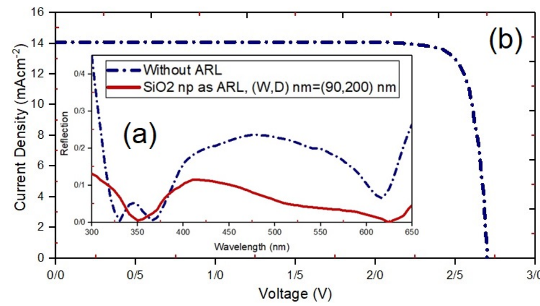

Fig. 4. a) Reflection for two structures, and b) Structure *II*'s J-V curve.

$(t_{WBG}, t_{NBG}) = (200, 105)nm$ in order to establish the current matching condition for both sub-cells, the photovoltaic parameters extracted from this diagram are: $(J_{sc}(mAcm^{-2}), V_{oc}(V), FF, PCE(\%)) = (12.32, 2.71, 0.87, 29.04)$. Which t_{WBG} and t_{NBG} parameters are the thickness of the absorber layers of the top and bottom sub-cells, respectively. These results have been confirmed by [2]. Fig. 3a depicts the J_{sc} of the top sub-cell for the diameter (D) and center-to-center distance (W) of the SiO_2 nanospheres in structure *II*. The results indicate that, assuming the t_{WBG} is constant, the maximum J_{sc} of top sub-cell ($14.07mAcm^{-2}$) is obtained for $(W, D) = (90, 200)nm$. In order to achieve the current matching condition of two sub-cells in structure II with optimal parameters, the t_{NBG} in terms of J_{sc} of the bottom sub-cell is drawn in Fig. 3b. It is evident that 224 nm is the necessary t_{NBG} to create this condition. Therefore, SiO_2 nanoparticles with the properties of $(W, D) = (90, 200)nm$ as well as $(t_{WBG}, t_{NBG}) = (200, 224)nm$ are required to establish the matched J_{sc} between top and bottom sub-cells of $14.07mAcm^{-2}$ for structure *II*. The reflection parameter in two structures is displayed in Fig. 4a. Structure *I*, where the ARL is not incorporated into the structure, is shown by the blue curve. The value of this parameter for the proposed structure with the addition of SiO_2 nanosphere is depicted by the red curve. It is clear that the addition of nanoparticles reduces the quantity of reflection in the 300–650 nm wavelength range. This is because low-RI SiO_2 material is used, which can function as an AR coating. The J-V characteristic curve of structure II is shown in Fig. 4b for nanoparticles with optimal parameters under current matching condition between the top and bottom sub-cells. The following photovoltaic parameters are taken from this diagram: $(J_{sc}(mAcm^{-2}), V_{oc}(V), FF, PCE(\%)) = (14.07, 2.71, 0.87, 33.17)$. By comparing Fig. 2 and Fig. 4b, we find that by adding the SiO_2 nanospheres as ARL on top of the proposed structure, the amount of matched J_{sc} increases from $12.32mAcm^{-2}$ to $14.07mAcm^{-2}$, which is greater than the J_{sc} of the reference structure by 14.20%. Therefore, the PCE increases from 29.04 % to 33.17 %, which is 14.22% higher than before.

IV. CONCLUSION

In this paper, the opto-electrical features of lead-free 2T AP-TSC with and without nanosphere arrays as ARL as structures II and I were compared together. An ARL made of SiO_2 nanosphere arrays with optimal parameters D and W was used to improve the PCE of reference structure (structure *I*). The optimum $(D, W) = (90, 200)nm$ was obtained to achieve the maximum J_{sc}. In order to achieve the current matching condition, $(t_{WBG}, t_{NBG}) = (200, 224)nm$ is needed after the addition of nanoparticles to the top of the proposed structure. Compared to structure *I*, structure *II* had a 14.20% and 14.22% increase in the J_{sc} and PCE parameters, respectively. Finally, a lead-free AP-TSC was proposed with a PCE of 33.17%.

REFERENCES

[1] S. Yoon, J. Ryu, S. Cho, H. D. Kim, J. Lim, J. S. Cho, J. Park, and D.-W. Kang, "Lead-free, sn-based all-perovskite tandem solar cells with an efficiency over 15%," *Small*, p. 2501876, 2025.

[2] M. Moradbeigi and M. Razaghi, "Optical–electrical simulation and optimization of an efficient lead-free 2t all perovskite tandem solar cell," *Renewable Energy*, vol. 220, p. 119723, 2024.

[3] B. K. Kumar and N. D. Gupta, "Nanostructured anti-reflection coating for absorption enhancement in perovskite silicon tandem solar cells," *Optical Materials Express*, vol. 14, no. 1, pp. 139–154, 2024.