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DESIGN AND SIMULATION OF EFFICIENT PEROVSKITE TANDEM SOLAR CELL

A. Hoque[1], **S. Debnath**[1] **and M.A. Matin**[2]

[1] Dept. of EEE, Chittagong University of Engineering and Technology, Chittagong-4349, Bangladesh
[2]IET, Chittagong University of Engineering and Technology, Chittagong-4349, Bangladesh
ashraful.ash1@gmail.com, sumitdebnath.cuet@gmail.com, imamatin@yahoo.com

Abstract- *The tandem solar cells combined with silicon and perovskite absorbers have the potential to outperform the high efficiency silicon single junction devices. Si solar cell has been stuck around 25 % efficiency for the last 15 years. To surpass this efficiency limit of the single junction solar cell tandem approach has been taken. The organic-inorganic lead halide Perovskites material have been shown significant role in the photovoltaic (PV) technology for over a decade due to its highly increasing efficiency. Methylammonium lead iodide based cells, have the potentiality for tandem cells that can act as absorber layer which has a band gap of 1.65 eV which is compatible to be paired with silicon (Si) solar cell with an energy gap of 1.124 eV as a tandem solar cell. In this work a high performance Si-perovskite tandem cell was designed on wx-AMPS software. The efficiency for the tandem cell was found 33.60 %, (V_{oc}= 1.42 V, J_{sc}= 26.58 mA/cm^2, FF= 88.56 %) with temperature coefficient of 0.045 %/º C.*

Keywords: Perovskite solar cells, Silicon solar cells, tandem solar cells, tunable bandgap, wx-AMPS simulation.

1. INTRODUCTION

Energy is a very important factor of global economy. A sustainable supply of energy is a key to the development of modern society and economy. With the development of the civilization day by day the consumption of energy is also increasing. Because of the limitation of the conventional energy sources in near future we have to rely on another alternative energy sources. One of the best alternatives of the future energy crisis can be the solar cell technology. One of the limitation of the solar cell technology is its low efficiency and high cost. Si solar cell has been stuck around 25 % efficiency for the last 15 years. According to NREL the record efficiency of Si solar cell on 2019 was 27.6% [1]. This efficiency is near the Shockley-quiesser limit. High efficiency with low cost solar cells have become the challenge for the researchers. In the recent years an emerging solar cell material name perovskite have shown a remarkable performance in photovoltaic field. By changing and varying the architecture of the device their efficiencies have been improved from 3.8% in 2009 to as high as 23.7% in the recent year [2]. Tandem or multi-junction approach can be taken to surpass the limit of single junction solar cell. Because of the growing energy needs it has become a challenge to increase the efficiency of the solar cell. In a tandem or multi-junction cell two or more different types of cell are sandwiched. It enables the cells light absorption range as well as efficiency. Normally in a tandem cell upper layer has the high band gap and the lower portion cell have smaller band gap. The top cell (wide-bandgap semiconductor) absorbs the low energy photon and the bottom cell captures the high energy photon. The crystalline silicon (c-Si) solar cells seem to be a complementary choice for the bottom cell because of their small band gap, low cost of manufacturing, and high efficiency [3]. Several materials including group III-V semiconductors and perovskites can be used as the top cell of the tandem cell. Group III-V material deposition are expensive. They also provide high efficiency. Because of expense their application is limited to the spacecraft operation. On the other hand in the recent few years the organic-inorganic halide perovskite have drawn the attention because of their increasing efficiency and also lower cost. Moreover they have tunable high band gap, direct band gap, high absorption coefficient, long carrier diffusion length, and bipolar carrier transport characteristics. Because of the high absorption capability around 500 nm thick perovskite layer is sufficient to absorb a very high portion of the incident light. The Perovskite cell demonstrated higher built in voltage as well as higher open circuit voltage (V_{oc}), relative to the bandgap of l.6 eV, than a single c-Si junction under the sunlight visible spectrum (400- 800nm) [4]. All these properties have made the perovskite suitable for both single junction and multi-junction process [5-6]. A perovskite have a unique crystal structure which consists of formamidinium with multiple cations and mixed halide ions. The perovskite

cell includes hybrid organic-inorganic lead or tin halide based material [7]. Perovskite was first introduced in 2009. In early 2012 the semiconductor property of the perovskite have been introduced by the scientists. After that his material have become to be used in the solar cell [8]. Several research have been made on tandem perovskites cells including silicon bottom cell and in the recent years impressive progress has been obtained, while higher bandgap perovskite will be used as the top cell. As a result absorption range will be increased and more power conversion efficiency will be obtained. This tandem design has a detailed balance limit of 40%, thus, overcoming the Shockley-Queisser limit of silicon single junctions [9].

This study focused on the simulation of a c-Si/perovskite tandem cell for improved output efficiency by changing the material thickness and using proper tunnel junction material for the optimization of the cell. The simulation was carried on wx-AMPS simulation software a newly developed solar cell simulation software based on the original AMPS code [10].

2. SIMULATION SOFTWARE

This work was carried on wx-AMPS software. wx-AMPS is a substantially new solar cell simulator for modeling one-dimensional devices composed of various materials. It accepts the same input parameters as AMPS, conforms to similar physical principles and numerical descriptions of defects and recombination and adds the effects of tunneling currents based on two different tunneling models. wx-AMPS is written in C++ and includes a number of revisions to the basic algorithm. Across-platform C++ library, wx Widgets, is used to develop a new graphical user interface (GUI) to allow quick data entry and enhanced visualization of results for comparison and analysis [10].

3. DESIGN AND SIMULATION

In this part the device structure and the methodology used for obtaining the Si/Perovskite solar cell characteristics are described. For a photovoltaic device which have two different bandgap material the band gap of the top cell have to be larger than the bottom cell for the desired operation [11]. From the previous section, we knew that, Perovskite has the ability to tune band-gap ranging from 1.6 to 1.9 eV (which is higher than Si). It is close to the band-gap of top cell of an optimum two bandgap system. Alongside the value of bandgap the properties of the absorber layer of the top cells also plays an important role to reach an optimum performance [12]. For the demonstration and obtaining current voltage (I-V) or current-density voltage (J-V) characteristics of the two terminal tandem solar cell, we first optimized the two sub-cell individually. The optimization was done mainly by varying thickness of different layers. For the Perovskite as top cell optimization is also done by varying band-gap. $CH_3NH_3PbI_3$ ($MAPbI_3$) Perovskite was selected for the top absorber cell since it has a higher band-gap of 1.65 eV. $MAPbI_3$ has high current density (J_{sc}) and thus has high power conversion efficiency. The c-Si structure consists of a front contact, n-type c-Si emitter layer, p-type c-Si main absorber layer, heavily doped p-type c-Si BSF and metal back contact. Lower energy photons are passes through the top Perovskite cell without and any absorption and after reaching the bottom silicon absorber layer they are absorbed by this layer which covers a wide spectral range depending on the band-gap of c-Si. In the n-p-p+ structured solar cell, the n-type emitter layer is highly doped. These n-type emitter layer and the p-type BSF act as ETL and HTL respectively. The c-Si absorber layer is comparatively thick and it's light absorption coefficient is high [13].

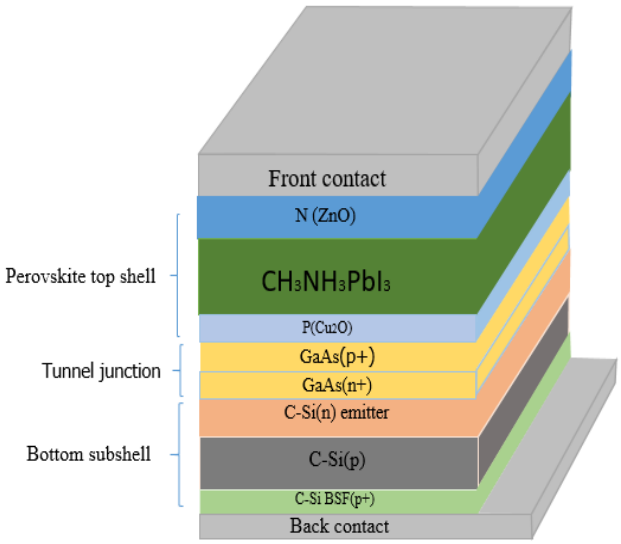

Fig. 1: Schematic view of proposed Perovskite/Si tandem cell.

For the tandem structure, these two sub-cell are combined matching different physical parameters. The Perovskite Solar Cell is employed with an n-i-p structured device where the intrinsic $MAPbI_3$ (i-Perovskite) is the main absorber layer and the transparent conductive oxide (TCO) of n-type ZnO is the hole transporting layer (HTL) and the p-type Cu_2O is the electron transporting layer (ETL). The Cu_2O has also good transparency, high hole mobility and good chemical stability. ZnO has an energy-band structure and physical properties similar to those of TiO_2. But ZnO has substantially higher electron mobility than that of TiO_2, which would make it an ideal kind of n-type material. Therefore, Cu_2O as HTL and ZnO as ETL are widely utilized to Perovskite solar cells.

At first the single junction silicon and perovskite cells were optimized by using thickness and bandgap optimization process for different layers of the cells. After that those c-Si and the perovskite layers are combined together for the proposed tandem configuration. Here in the tandem cell the thickness of the two absorber layers were again optimized along with the tunable bandgap of Perovskite layer. For the tandem cell modelling and optimization, the thicknesses of the different layer were varied keeping all other properties as constant as previous cells.

In a two terminal tandem cell, internal electrical connection between the two consecutive sub-cells must be provided. These electrical connections are liked to be

ohmic contact. These internal ohmic contacts (IOCs) preserve some properties like high conductivity therefore low resistivity, high optical transparency. The most significant property that IOCs must have is their high pick current density. These IOCs are made by adopting two methods. One is tunnel junctions (or tunnel diode or recombination layers) and the other is metal interconnects. But metal interconnects are not preferable because of their complex processing and poor device efficiency [14]. So these tunnel junctions also must conserve the above mentioned properties. As previously explained the c-Si cell was used as the bottom cell and the perovskite was used as the top cell with GaAs tunnel junction.

TABLE 1. Input parameters Perovskite-Si solar cell.

Parameters	**n ZnO**	**$CH_3NH_3PbI_3$**	**P Cu_2O**	**c-Si (n) emitter**	**c-Si (p)**	**c-Si BSF (p+)**
Thicknes	10nm	9µm	0.7 µm	50nm	250 µm	30nm
Bandgap (eV)	3.37	1.65	2.1	1.124	1.124	1.124
Electron affinity (eV)	4.35	3.93	3.6	3.9	4.05	3.9
Permittivity	10	30	10	11.9	11.9	11.9
Nc (cm^{-3})	2.22 x 10^{18}	2.5 x 10^{20}	1x 10^{19}	2.8 x 10^{19}	2.8 x 10^{19}	2.8 x 10^{19}
Nv (cm^{-3})	1.78 x 10^{19}	2.5 x 10^{20}	1x 10^{19}	2.6 x 10^{19}	2.6 x 10^{19}	2.68 x 10^{19}
Electron mobility (cm^2/Vs)	100	50	30	1250	1010	1212
Hole mobility (cm^2/Vs)	25	50	30	443	443	421
Nd (cm^{-3})	1 x10^{20}	0	0	8 x 10^{20}	0	0
Na (cm^{-3})	0	0	2.5 x 10^{16}	0	5 x 10^{18}	9.5 x 10^{20}

We can see the different input parameters for the tandem cell. By putting these values the proposed tandem cell was simulated.

4. RESULT AND DISCUSSION

In this section, the performance characteristics of the designed cells have been shown and analyzed that we achieved from the simulation. The optimization of the designed cells was done by varying the thickness and band-gap of the respective layers. We first designed and optimized the single junction perovskite and single junction Si cell. Then we combined the two single junction cells incorporated with GaAs tunnel junction. The proposed tandem cell was then optimized with respect to absorber layer thickness and band-gap. The I-V curve of the optimized perovskite cell is shown in Fig. 2. The figure shows the efficiency of the cell to be 23.1% with V_{oc}=0.978 V, J_{sc}=28.05 mA/cm^2, FF=84.24%.

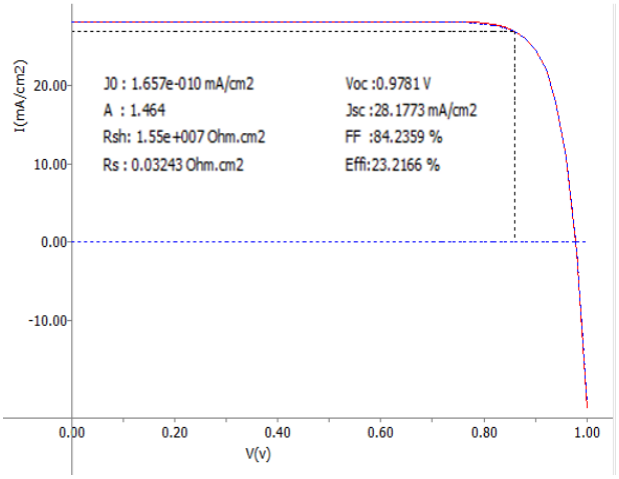

Fig. 2: Simulated I-V curve of single junction perovskite cell obtained from wx-AMPS.

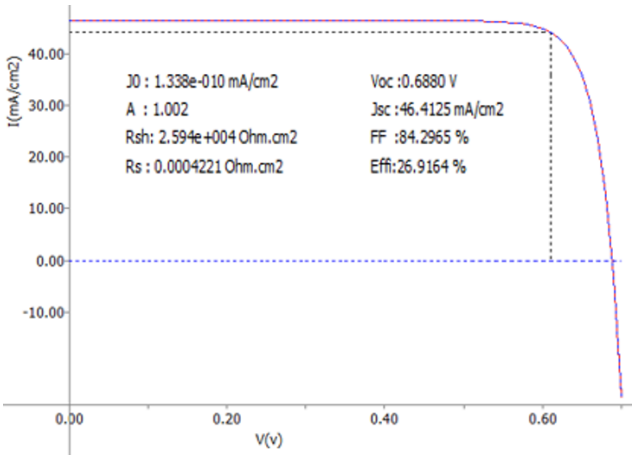

Fig. 3: Simulated I-V curve of single junction Si cell obtained from wx-AMPS.

In the Fig. 3 the simulation result of the optimized single junction Si cell is shown. From the figure we can see the efficiency of the cell to be 26.97% with V_{oc}= 0.6880 V, J_{sc}= 46.4279 mA/cm^2, FF= 84.2971%.

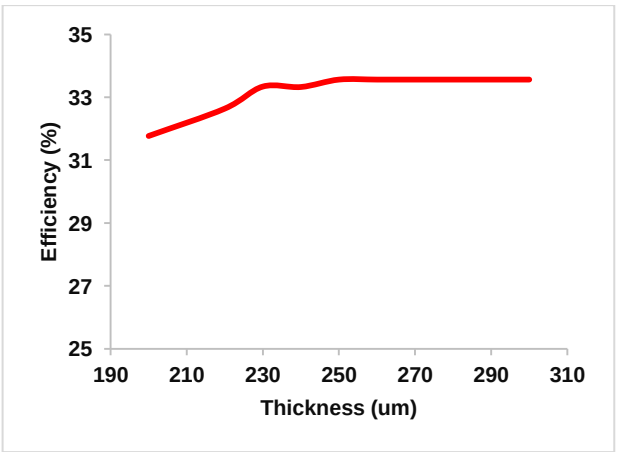

Fig. 4: Thickness optimization of the Si absorber layer

After optimizing the two single junction cell we combined the cells to design our proposed tandem cell and also optimized the final cell with respect to absorber layer thickness and band-gap. The optimization of the cell is shown in fig. 4 & 5.
The Fig. 4 shows the efficiency vs thickness curve. Optimization point is chosen from this curve and the selected thickness is 250 µm for the Si absorber layer.

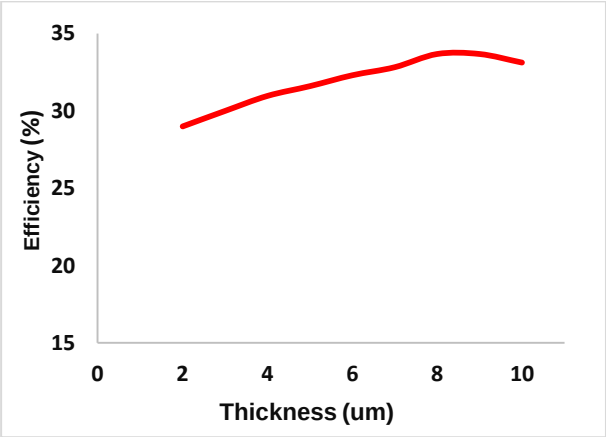

Fig. 5: Thickness optimization of the Perovskite ($CH_3NH_4PbI_3$) absorber layer

The Fig. 5 shows the efficiency vs thickness curve. Optimization point is chosen from this curve and the selected thickness is 8 µm for the Perovskite absorber layer.
The simulation result of the designed tandem cell is shown in the Fig. 6.

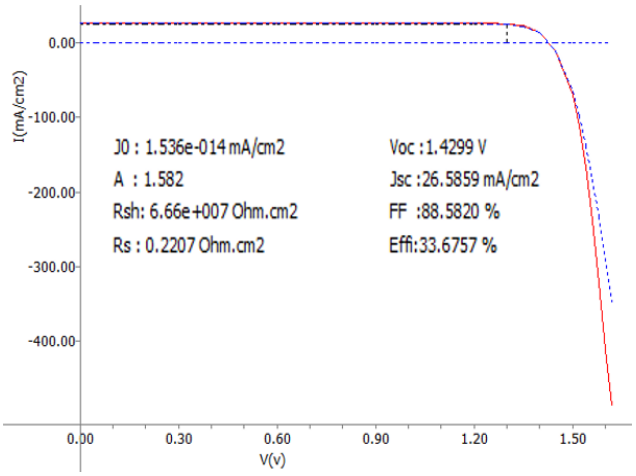

Fig. 6: Simulated I-V curve of the designed tandem cell obtained from wx-AMPS.

From the Fig. 6 we have seen the efficiency of the tandem cell is to be 33.60% with a good fill factor of 88.56%. The short circuit current density is J_{sc}= 26.58 mA/cm^2 and the open circuit voltage is V_{oc}= 1.42V.
The temperature coefficient of the tandem cell has been also analyzed and demonstrated to be stable analytically.

5. CONCLUSION

In conclusion, a theoretical framework on two terminal Perovskite/Si tandem cell modeling has been demonstrated in this session. From our design we obtained the value of the efficiency to be 33.6% and it is the highest simulation based efficiency. The other performance parameters are as V_{oc}= 1.42V, J_{sc}= 26.58 and FF=88.56%. The total thickness of the tandem cell was in the order of 259 µm. The optimum thickness for the perovskite absorber layer was 8 µm and the optimum thickness for the Si absorber layer was 250 µm and the optimized band-gap of the perovskite material was 1.65 eV. From the analysis we can say that the efficiency of the tandem cell can be further improved by inserting more than two junctions of compatible cell materials and suitable tunnel junctions between the successive sub-cells. Finally, we can say that tandem cell is a window opening process in the sector of renewable energy and there is a possibility of huge research in that field to meet the emerging energy demand.

6. REFERENCES

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7. NOMENCLATURE

Symbol	Meaning	Unit
Voc	Open Circuit Voltage	(V)
Jsc	Short Circuit Current	(mA/cm^2)
FF	Fill Factor	(%)