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ORIGINAL RESEARCH

Design and modelling of G–ZnO nanocomposite electrode for a-Si:H/μc-Si:H micromorph solar cell

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Abstract Solar photo voltaic cell (PVC) has shown colossal potential in reducing the cost of electricity and is considered to be one of the cleanest green forms of renewable energy. The current standard material for transparent electrodes in solar PVC is indium tin oxide (ITO). Owing to the high cost of ITO, scarcity and chemical instability of indium, graphene has been proposed as a potential alternative by scientists. This paper, suggest that replacing ITO with mono-layer graphene in amorphous silicon (a-Si) solar PVC yields comparable performance. This paper further explores standard multiple junctions tandem a-Si:H/μc-Si:H micromorph solar PVC (msPVC) for better efficiency and proposes the use of graphene (G)–zinc oxide (ZnO) nanocomposite electrode based msPVC (G-ZnOmsPVC) for better absorption. The modelling and characterisation is done on SILVACO-Atlas virtual fabrication tool. The results reveal that the G-ZnOmsPVC manifests higher power conversion efficiency and absorption spectrum than that of traditional msPVC.

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1 Introduction

Solar PVC is a solid-state (p–n junction) electrical device [1] that converts the energy of light (photons) directly into electricity (DC) using photovoltaic effect. This process requires materials having high absorption coefficient to excite electrons (exciton) to higher energy state leading to current generation. Solar PVC [2] structure is shown in Fig. 1 encapsulating a number of layers from the light-facing transparent conducting electrode (TCE) side to the dark back reflector as given under.

The variegated layers of solar PVC impacts recombination rate, absorption coefficient [3] and wherefore affects power conversion efficiency. This impact can be analysed as the spectral response (£) rate given as Eq. (1) which is contingent on the wavelength of the incoming light, material used in absorption as well as other layers and is given by:

$$£ = \frac{\text{Electric current}}{\text{Irradiance}}, \quad (1)$$

For the better spectral response rate the front layer of solar PVC is stacked as a transparent conducting oxide (TCO) layer. The ideal TCO should be fully transparent (with transmittance $> 80\%$) for absorbing wide range of wavelengths, as well as have metal-like conduction properties. Most common TCE used today are based on doped metal oxides, such as ITO, doped zinc oxide and fluorine doped tin oxide. Amongst which ITO is most commercially used oxide with high electrical conductivity, better transparency and easy deposition on thin

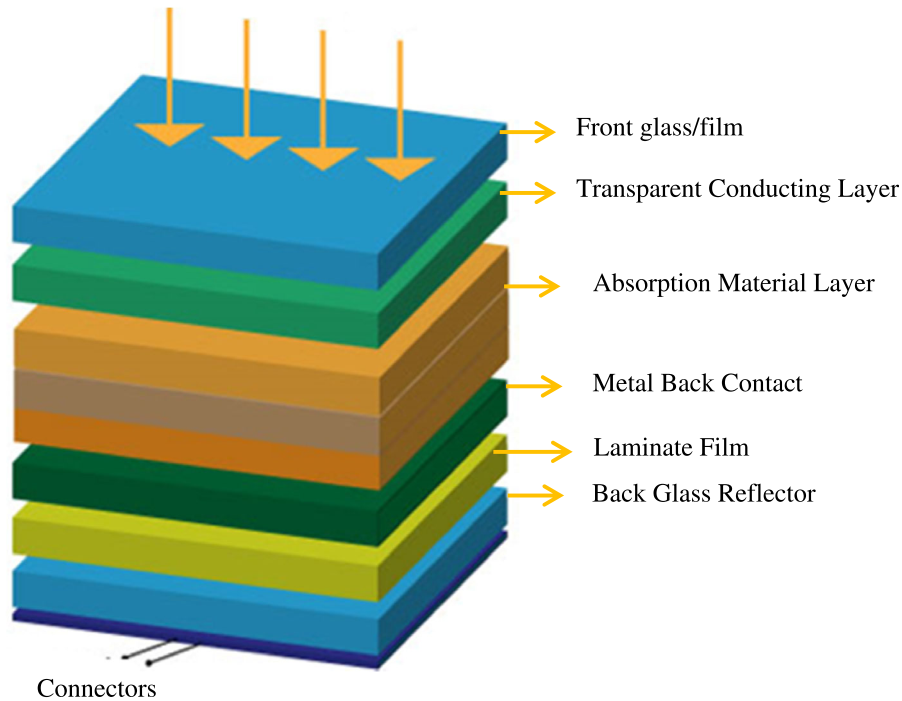

Fig. 1 Solar PVC layers from the light-facing TCE side to the dark back reflector structure

film. However, the relatively high cost, limited opto-electronic performance, and mechanical brittleness exclude ITO from many applications. Recently, research progress in nanomaterials [4] has opened new areas for alternative TCE as Graphene. This single layer of atom of carbon hexagon called graphene [5] is seeking a lot of attention of researches because of its uniqueness and nonpareil properties. Other factors which makes it a better alternative:

- The effective charge collection via low sheet resistance.
- Graphene only reflects $< 0.1\%$ of the incident light in the visible region, rising to $\sim 2\%$ for ten layers.
- The work function lies between 3 and 5.5 eV which makes it suitable for photovoltaic layers with different energy levels.
- Enhanced solar cell efficiency.
- Graphene act as a recombination contact for holes and electrons which avoid the building of charge and hence reducing the open circuit voltage.

These exceptional electronic qualities and the outstanding electron/hole-transport properties of individual graphene crystallites have successfully attracted photovoltaic researchers to replace the existing materials in numerous ways (as TCE/blocking layer/hole transport layer/electron transport layer).

Graphene withal to these properties exhibits high tensile strength due to which it can be successfully used with silicon (Si) solar PVC [6, 7]. This cell comes up with high efficiency and the disadvantage of increased cost, giving rise to need of removing unnecessary material especially in active layer; this generated the idea of thin film solar PVCs. The thin film solar PVCs besets the drawbacks of:

- low power conversion efficiency,
- light induced degradation,
- high deposition rate,
- insupportable mass production,
- material cost.

As a solution to above mentioned stumbling blocks faced by thin film, tandem or multi-junction micromorph solar PVC has emerged as a panacea. Micromorph solar PVCs are based on a multi-junction architecture and incorporate two solar PVCs which are stacked on top of each other. While the thin a-Si top [8] cell efficiently absorbs the blue light of solar spectrum, red and near-infrared light gets absorbed by the thicker microcrystalline silicon (μc-Si) bottom cell. This enables tandem solar PVC to embed a wider range of the solar spectrum resulting in increase of the absorption coefficient. By applying two materials in a tandem or multi-junction

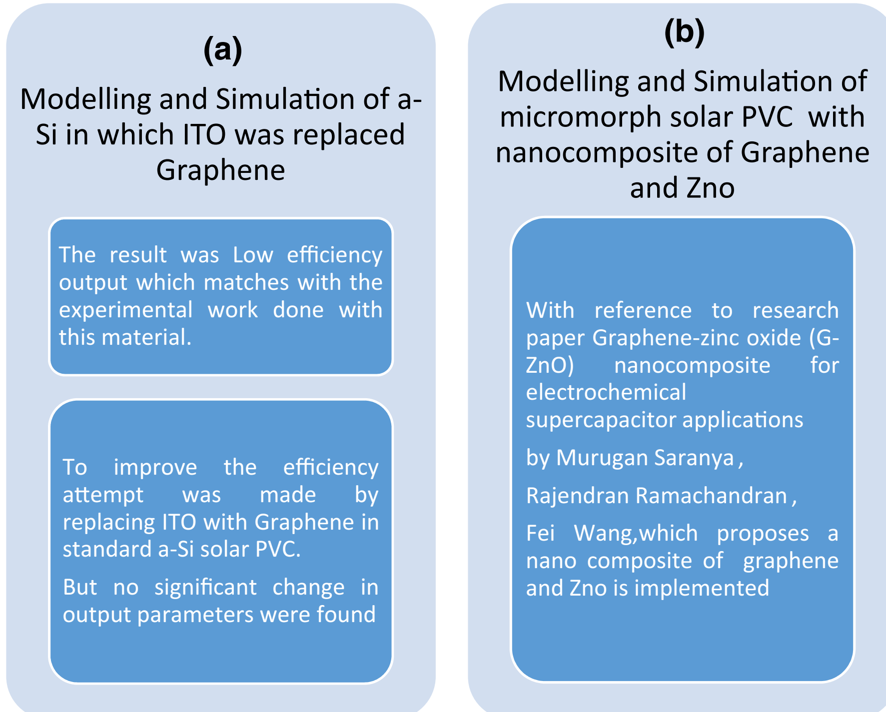

Fig. 2 Research work in this paper

cell, an even wider spectrum can be captured [9]. To further reduce the effect of induced light degradation and better absorption the hydrogenated amorphous silicon (a-Si:H) is proposed.

The research work in this paper as shown in Fig. 2; firstly investigates, the electrical and optical potential of a graphene surface-covering electrode. Secondly, examines its possibility as a transparent electrode for planar a-Si based solar PVCs and determines that graphene, in a suitable multilayer structure with anti-reflecting properties can enhance or at least compete with the absorption of an ITO electrode [10], for an a-Si active layer with various thicknesses. Thirdly, this research besides investigating graphene potential as a surface-covering electrode also evaluates its application as a nanocomposite with zinc oxide (ZnO) as G–ZnO on micromorph solar PVC.

The results extracted claim increase in wavelength of light spectrum being absorbed in broader range. This paper proposes a G-ZnOmsPVC with the incorporation of G–ZnO nanocomposite [11, 12] within micromorph solar PVC structure for better photon harvesting on wider range of wavelength. For these studies, modelling and simulation is done on virtual fabrication tool SILVACO-Atlas.

The next section gives an overview of literature survey and problem identification.

2 Literature survey and problem identification

S. no.	References	Proposal	Problem identification with results
1.	Chowdhary et al. [10]	This paper investigates the role of graphene in organic PVC and DSSC for transportation of carrier The paper concludes Graphene as TCE alternative replacement of ITO/FTO layer for remarkable optical transmittance	For large scale production, fabrication of single layer of graphene with controlled electrical and optical parameters is a challenge Graphene suits as a transparent conductive layer electrode in inorganic or organic solar PVCs, as an intermediate layer in tandem solar PVCs and as a blocking layer in perovskite solar PVCs
2.	Tavakoli et al. [31]	This paper uses Graphene in the form of scaffold as an interface layer between absorption layer and electron transfer layer in perovskite solar cell Reduced graphene scaffold (rGS) enhances the carrier transportation and shows 27% increase in the performance as compare to conventional solar cells	Use of ZnO and TiO_2 shows only 10% improvement in the performance of the cell Better alternatives needed to increase overall cell efficiency
3.	Meillaud et al. [29]	This paper reviews current attainments and various challenges in thin-film a-Si and nanocrystalline solar PVC and their alloys with: (1) inclusion of absorber layers, which shows better results in terms of absorption rate and J_{sc} (short circuit current densities); (2) enhanced photon harvesting with multi-scale texturing of photovoltaic substrates	This results show that in recent years, at both the cell and large-area module level, output power conversion efficiencies of over 13 and 12%, are reported
4.	Lu et al. [15]	In this paper Graphene is used as cathode material for dye sensitized solar cell to provide high performance	The major disadvantage of graphene is its susceptibility to environment of oxidative as inferred in this paper
5.	Avrutin et al. [32]	This paper analysis the present and future technical prospectus of micromorph solar PVC. How journey from c-Si to thin films have benefitted in terms of cost and efficiency. Various light trapping strategies and interfacing engineering to enhance photon management has been reviewed	a-Si has shown only marginal improvement in terms of efficiency with limitations hard to recover The micromorph cell has proved better performance capabilities in comparison to a-Si solar PVC module Need of micromorph Si solar PVCs to ameliorate their performance, while keeping the manufacturing cost low
6.	Kuang et al. [14]	The photovoltaic behaviour of graphene based GaAs junction solar cell on various parameters is studied in this paper Graphene compatibility multi-junction devices is also investigated	GaAs has high direct band gap and is highly resistive to radiation so there is need to combine a material that is well suited with it for large scale applications The device incorporating is not able to provide high efficiency
7.	Saranya et al. [15]	Fabrication of G–ZnO nanocomposites G–ZnO nanocomposites exhibited better capacitive behavior (122.4 F/g) in comparison to reduce graphene oxide (rGO)—(102.5 F/g) and graphene oxide (GO)—(2.13 F/g) and at 5 mV/s scan rate	Results showed G–ZnO hybrid nanocomposite can be widely used in supercapacitor application as a propitious electrode
8.	Singh and Nalwa [18]	Graphene in this paper is proposed in organic photovoltaic cell as counter electrode, ETL layer, HTL layer and electron blocking layer	Need to have environmental degradation and cost effective solution, graphene is being used in photovoltaic industry The performance of graphene largely depends on various parameters such as thickness, passivation and heteroatom doping
9.	Lin et al. [33]	With the help of electrophoretic deposition, a new hybrid material is being fabricated for dye sensitized solar cell by introducing MoS_2/reduced graphene oxide (RGO) nanocomposites with carbon nanotubes (CNTs) The use of conductive network of CNT gives an extra access for transportation of electrons and increases the charge transfer rate	The structure with MoS_2/RGO-CNTs achieves the efficiency of 7.46% as compared to costly PCE (7.23%) The process of fabrication is complicated one

S. no.	References	Proposal	Problem identification with results
10.	Hafezi et al. [34]	The paper proposes the use of p–i–n and n–i–p micromorph solar cell deposited via plasma chemical vapour deposition (PECVD) technique, using a mixture of silane and hydrogen Micromorph thin film tandem cells are the most promising candidates for high efficiency and low cost photovoltaic cell	Conventional microcrystalline solar cells have morphological variety which makes it depends on temperature, thickness and other parameters There is a drawback of lack of reliability and reduction in the material flow and process energy
11.	Ray et al. [35]	The paper proposes a triple junction solar cell for better efficiency This paper shows how to achieve higher efficiency 32.84% using triple junction solar cell	More exploration is required in selecting of materials and the modelled solar cell is to be fabricated in physical lab and the efficiency of that physical lab should match with the simulated one
12.	Chander and Purohit [36]	This work presents a study on spectral response and external quantum efficiency (EQE) of mono-c-Si solar PVC. Spectral response meter was employed to perform the experiment in the wavelength range 350–1100 nm	The results exhibited better spectral response; maximum at 890 nm and decreased beyond this wavelength The EQE also showed an increase with wavelength; maximum at 590 nm
13	Bai et al. [28]	This paper studies the effect a-Si:H with I/N buffer layers and broader band gap passivation layer of Si oxide doped supporting layers	Addition of buffer layer have reported reduced recombination rate and enhanced carrier collection near interfaces PCE of 10.05% for single-junction μc-Si:H solar PVCs with a optimized thickness of 2 μm is reported Need of the device with better efficiency
14	Meillaud et al. [17]	This paper reports better PCE for micromorph solar PVC with Si-oxide-doped layers. With substrates having multi-scales textures, bilayers and ultraviolet nanoimprint lithography which results in better performance	With the increase in deposition of μc-Si:H for better efficiency cost of the device is also effectuated
15	Fang et al. [30]	This paper incorporates tunnel recombination junctions (TRJs) removing n-μc-Si:H layer in standard a-Si:H/μc-Si:H micromorph solar PVCs using chemical vapor deposition	Report of better efficiency (13.65%) for micromorph solar PVCs on ZnO:B substrates is mentioned Commercial production entails less complex fabrication process

The above table evinces that the absorption rate can be further improved, output power conversion efficiency (PCE) can be enhanced and light induced degradation in a-Si thin film solar PVC rectified.

- To augment PCE of thin film solar PVC micromorph tandem thin film technology is considered [13–15]. The advantage of using the micromorph approach for a-Si based thin film technology is that it the effect of induced light degradation (Staebler–Wronski effect) is reduced enhancing the efficiency.
- To enhance the light trapping of graphene-based thin-film solar cells [16], a simple two-layer composites structure of G–ZnO is proposed as transparent electrodes.

The next section reports on various modelling parameters considered for proposed G-ZnOmsPVC to provide a better solution in solar PVC market in terms of efficiency by reducing various losses encountered in a-Si thin film solar PVC.

3 Proposed G-ZnOmsPVC

In this work an integrated optical and electrical modelling is proposed by considering Graphene in a-Si and G–ZnO nanocomposite in multi junction or tandem thin film micromorph solar PVC as TCE [17]. Figure 3a represent solar schematic design of a-Si with Graphene replacing standard ITO [18] and various losses faced by this thin film solar PVC. The major impediment being induced light degradation of the device. This drawback of light degradation is covered in micromorph solar PVC; as they show an enlarged infrared response to solar spectrum. The greatest prospective of this solar PVC is in its amalgamation with a-Si top cell with μc-Si bottom cell in a tandem thin film solar PVC. Fischer et al. in their research have shown 13% efficiency potential with 10% stable efficiency of this “micromorph” solar PVC. An improved structure G-ZnOmsPVC is proposed. It exhibits better efficiency, absorption spectrum and cover-up the losses exhibited by thin film solar cell. Figure 3b represents proposed

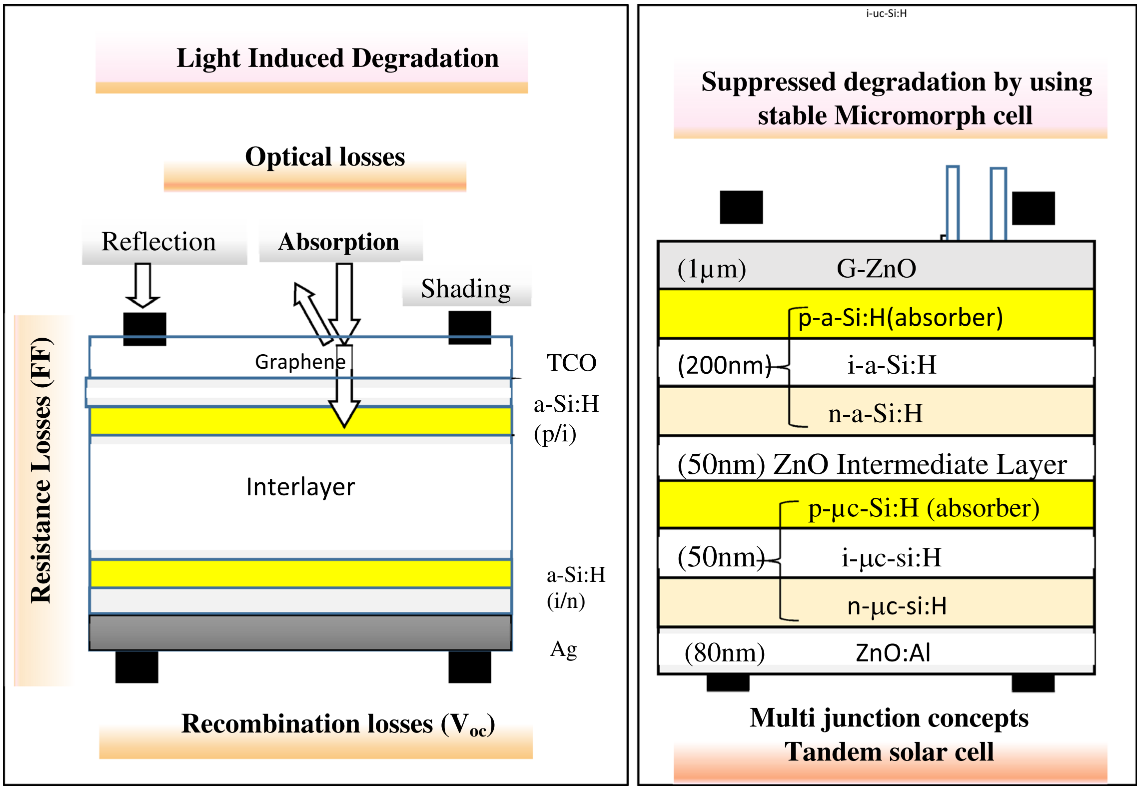

Fig. 3 **a** Schematic structure of Graphene as TCO a-Si solar PVC and **b** schematic structure of proposed G-ZnOmsPVC

G-ZnOmsPVC solar PVC schematic and mechanism to suppress degradation and losses.

In multi-junction micromorph solar PVC showed top and bottom cell produces the same current and faces losses like optical/resistance/recombination [19] which reduces its overall efficiency. The top micromorph cell is limited by the Staebler–Wronski effect due to induced light degradation and therefore light trapping and an intermediate reflector are needed to keep the thickness of the top cell low while increasing its current. The intermediate reflector (IRL) is usually a layer of zinc oxide (ZnO intermediate reflector: ZIR) or silicon oxide (SiO_x intermediate reflector: SOIR) [20] between the top and the bottom cell.

The proposed G-ZnOmsPVC structure incorporates a G–ZnO as TCE [21] on a-Si thin-film solar PVCs which allow multiple passes for trapping light more effectively. This will result in better absorption and quantify enhancement in charge collection factor. The enhance band of absorption quantifies edge surface and is capable to harvest more photon. The concept of anti-reflecting coating is been employed to reduce the impact of optical reflection losses which occur at air–glass interface.

The incorporation of top cell a-Si:H and bottom cell μc-Si:H allows the enhancement of the open-circuit voltage which helps in increasing the efficiency of the cell. Within the structure ZnO/Al is deposited as a superstrate. ZnO and Ag are used as back reflectors having realistic reflectance.

4 Simulation set up parameters

The simulation of the given structure is performed using SILVACO-Atlas tool [22, 23]. The structure used for the simulation is ZnO:Al/p-a-Si:H/i-a-Si:H/n-a-Si:H/ZnO/p-μc-Si:H/i-μc-Si:H/n-μc-Si:H/ZnO/Ag with graphene used as contacting electrode [24]. The urbach tail model is used along with the Tau–Lorentz dielectric function because of the complex refractive index of a-Si:H [25]. For the modelling of the interlayers between the device the method used is the addition of an electrode and using a lumped resistance with the help of contact name=com resist=1e16 command. The srh and auger model are being used for simulation. This auger model is necessary at high current densities. It takes into account the direct transition of three carriers. SRH model used for simulation stands for Shockley–Read–Hall model and is used for minority carrier lifetime and is used in most of the simulations [26, 27].

This helps the current to flow from anode to cathode and helps in preventing the flow of any other additional current

Table 1 Simulation parameters of different material used in modelling the device

Metal oxide	a-Si:H [24, 25]	μc-Si:H [24, 25]	ZnO [20]	Graphene [26, 27]
Band gap (eV)	1.7	1.16	3.4	0
Effective density of states (conduction band) (cm^{-3})	3×10^{20}	3.5×10^{20}	3.92×10^{18}	0
Effective density of states (valence band) (cm^{-3})	3×10^{20}	3.5×10^{20}	3.34×10^{18}	0
Electron mobility (cm^2/V s)	1	5	60	1603
Hole mobility (cm^2/V s)	0.1	0.5	3	330
Permittivity (F/m)	–	–	–	9.5
Affinity (eV)	–	–	–	7.5

than electrode. The work function is specified by using the syntax Work function = <value> for graphene range from 4.89 to 5.16 eV (Table 1).

4.1 Performance metrics

The performance metrics of a device refers to its evaluation and comparison parameters. To understand the performance metrics of a Solar PVC its electrical output parameters, current and voltage characteristics should be known. In this paper a systematic investigation of solar PVC parameters such as short circuit current density (J_{sc}),open circuit voltage (V_{oc}), fill factor (FF) and power conversion efficiency (η) for the devices is done. These parameters are formulated herewith:

1. Short-circuit current

The current which is flowing to the external circuit of a solar cell when the solar cell is short-circuited that current is referred to as short-circuit current. The short-circuit current (I_{SC}) is determined by the amount of photon flux is incident on the solar cell which in turn is estimated by the spectrum used.

2. Open-circuit voltage

The open-circuit voltage (V_{oc}) is a voltage that can be attained through a solar cell when the current through the external circuit is zero. This is the maximum voltage of a solar cell is given by Eq. (2). The open-circuit voltage is given by:

$$V_{OC} = \frac{nkT}{q} \ln\left(\frac{I_{SC}}{I_O} + 1\right), \quad (2)$$

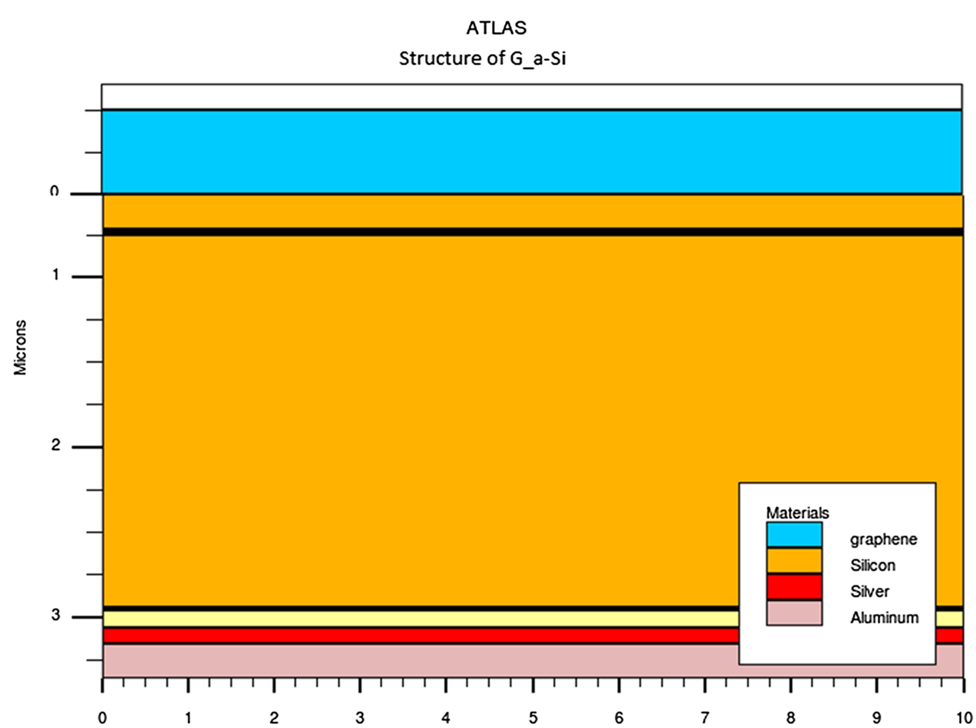

Fig. 4 Atlas structure model of a-Si solar PVC with graphene as electrode

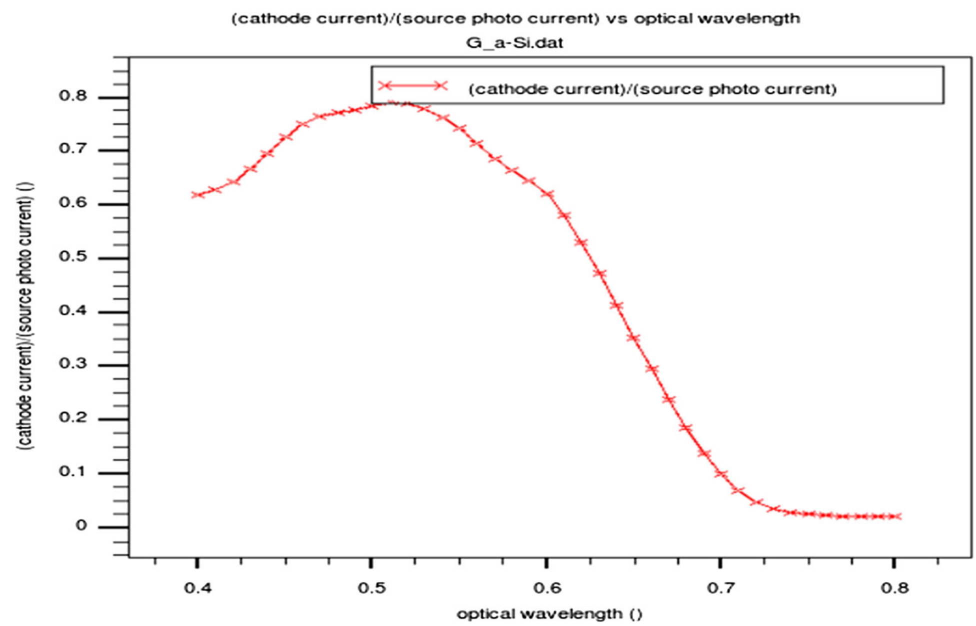

Fig. 5 Optical characterization of a-Si solar PVC with graphene as electrode

where I_o is the dark saturation current, I_{sc} is the short circuit current, q is the charge, N is the ideality factor, K is the Boltzmann constant, T is the temperature.

3. Fill factor

Fill factor is the ratio of the maximum power to the product of short-circuit current (I_{SC}) and open-circuit voltage (V_{OC}) as given in Eq. (3). The point on the I–V curve of the solar cell where maximum current and voltage i.e. maximum power (P_{MAX}) is attained that point is known as maximum power point:

$$FF = \frac{I_{MAX} \times V_{MAX}}{I_{SC} \times V_{OC}}, \quad (3)$$

where V_{MAX} is the voltage at maximum power, I_{MAX} is the current at maximum power, V_{OC} is the open circuit voltage, I_{SC} is the short circuit current.

4. Efficiency

The efficiency determines the actual performance of a photovoltaic cell. The efficiency is the measure of the output power to the input power. Mathematically, efficiency is the ratio of maximum power (P_{MAX}) delivered by the solar cell to the input power (P_{IN}) and is given by as

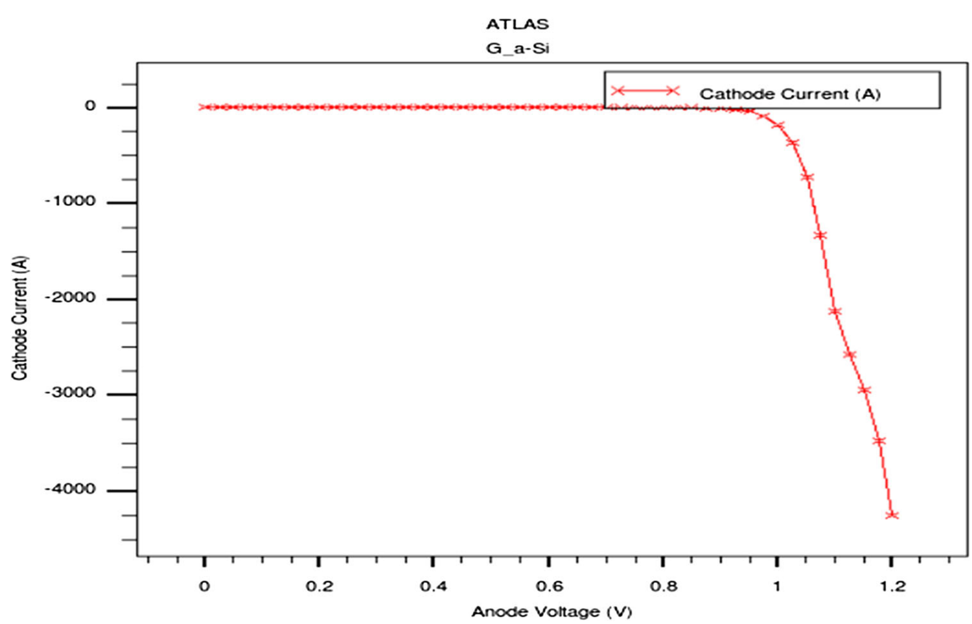

Fig. 6 I–V characteristic of a-Si solar PVC with graphene as electrode

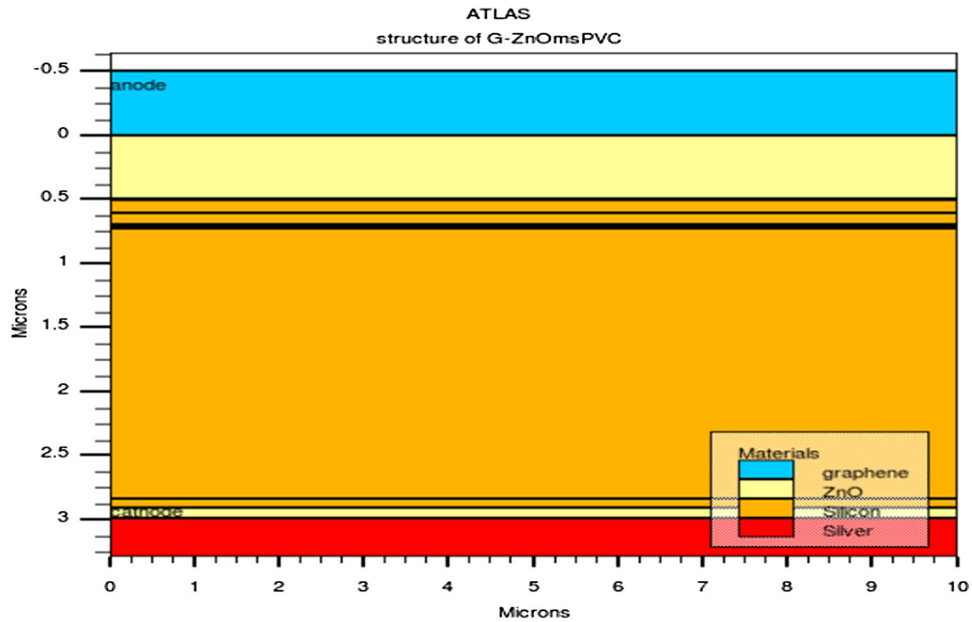

Fig. 7 Atlas structure model of G-ZnOmsPVC solar PVC with G–ZnO nanocomposite as electrode

defined in Eq. (4) where P_{MAX} can be further substituted with the product value of short circuit current, open circuit voltage and fill factor as shown in Eq. (5):

$$\eta = \frac{P_{MAX}}{P_{IN}}, \tag{4}$$

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{IN}}. \tag{5}$$

where V_{OC} is the open circuit voltage, I_{SC} is the short circuit current, FF is the fill factor.

4.2 Snapshot

This paper models and characterize both simulations of a graphene based a-Si solar PVC and tandem a-Si:H/μc-Si:H G–ZnO as electrode solar PVC. The snapshots show the modelling structure and simulation characterization in SILVACO-Atlas version 15 tools. Figures 4, 5 and 6 show the structure, optical and IV output characteristic of a-Si with graphene as an electrode and silver/aluminium as dark back reflectors. Figure 7 shows structure model with variation in acceptor concentration Fig. 8 of the proposed solar PVC.

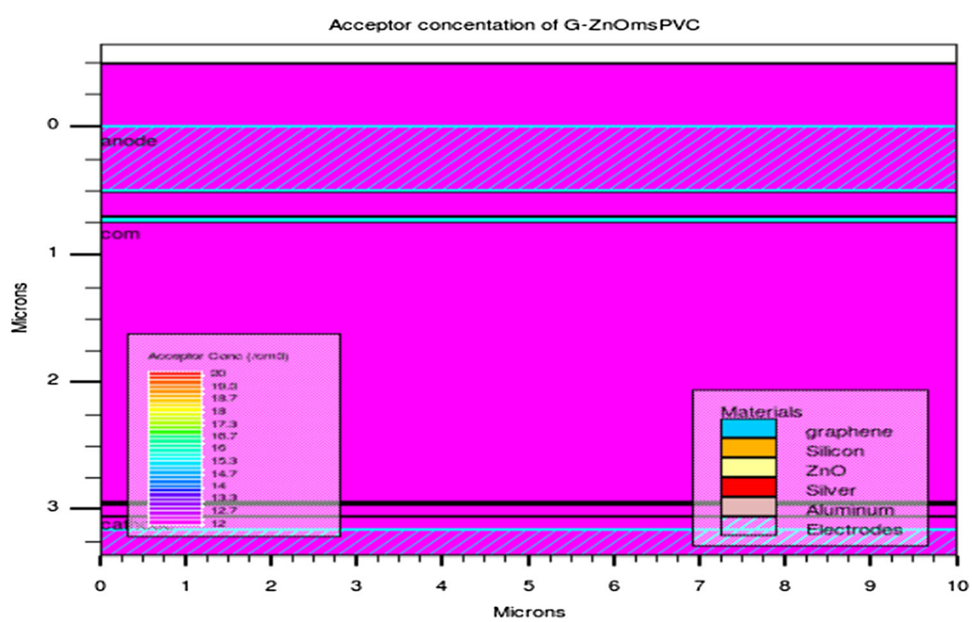

Fig. 8 Acceptor concentration model of G-ZnOmsPVC solar PVC

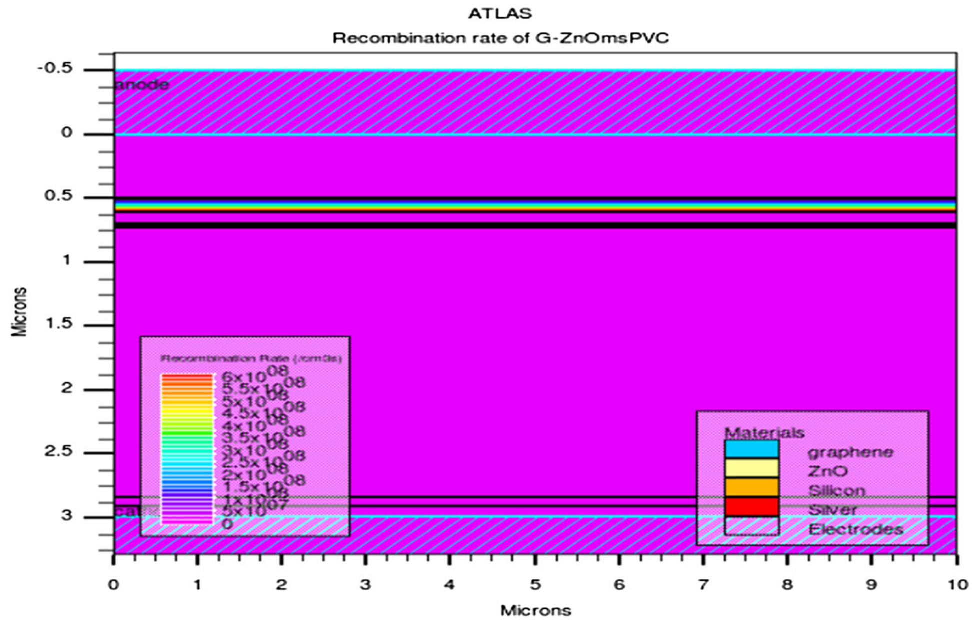

Fig. 9 Recombination rate analysis of G-ZnOmsPVC solar PVC

Figure 9 illustrates the recombination rate. The colophon in this figure expounds the solar PVC's recombination rates. The recombination rate is one of the important parameters to determine power conversion efficiency of the solar PVC; analysed by displaying the recombination in various layers of the G-ZnOmsPVC solar PVC. It is well clear in this figure that recombination rate is low where graphene is used and is least at the surface with gradual increases from topmost layers to back reflector silver layer.

The optical intensity of proposed G-ZnOmsPVC solar PVC, variegated layers is shown in the Fig. 10, which is different for different layers depending on incident irradiation. In this model the thin a-Si top layer efficiently absorbs the blue light whereas red and near-infrared light gets absorbed by the thicker microcrystalline silicon (μc-Si) bottom layer of the solar spectrum.

The optical characterization of the device gives idea about the photon absorption by plotting the spectral response encompassing of present photocurrent, photocurrent of source and current of cathode. Figure 11 exhibits the spectral response of proposed device top and bottom cell, respectively.

The I–V characteristic which is the superposition of I–V curve in dark with the illumination current of the proposed model is shown in Fig. 12. The region wise virtual fabrication modelling of proposed device is shown in Fig. 13.

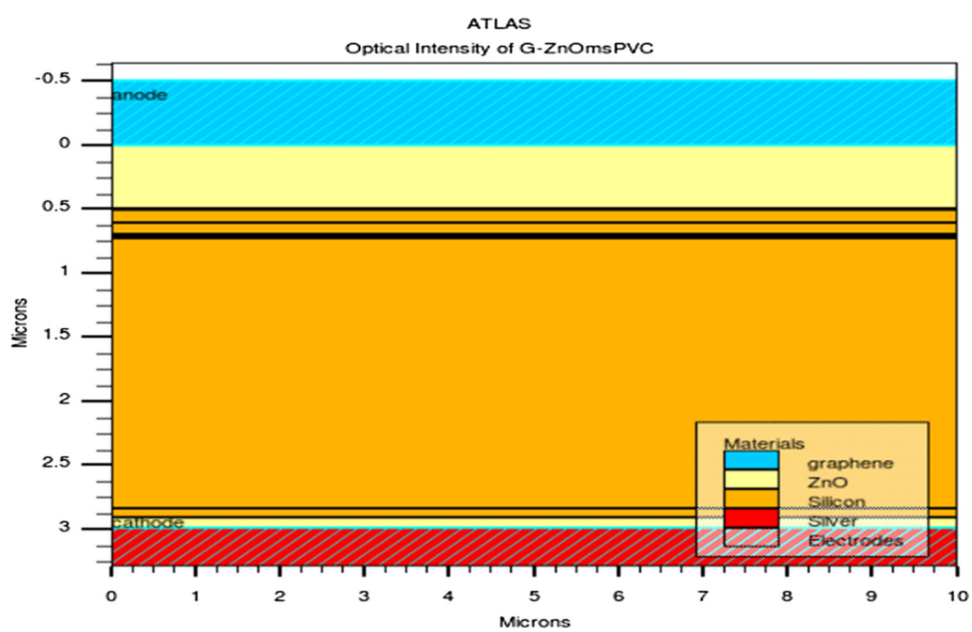

Fig. 10 Optical intensity analysis of G-ZnOmsPVC solar cell

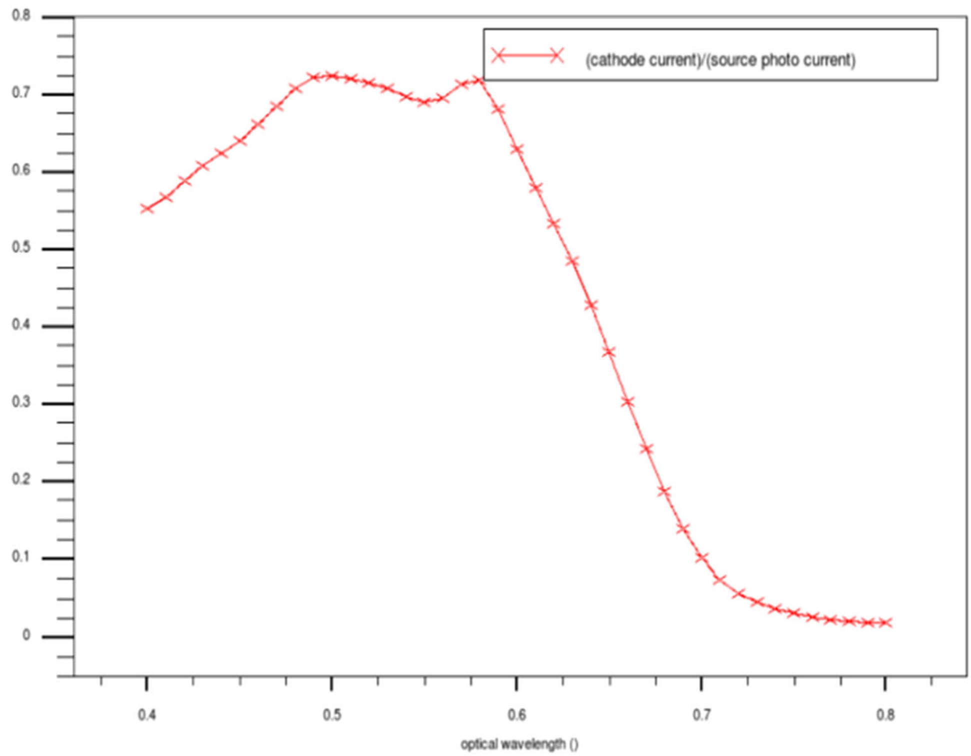

Fig. 11 Optical characterization of proposed of G-ZnOmsPVC solar cell

5 Comparison of proposed micromorph solar PVC model with existing micromorph models

The virtual fabrication tool SILVACO-Atlas is been used for the implementation of proposed G-ZnOmsPVC model. This virtually fabricated micromorph solar PVC, show better results in comparison to those published in Refs. [28–30]. Table 2 shows the various comparisons of this optimized design with other previous findings.

6 Results

The extraction of the charge carriers, open circuit voltage, fill factor of the tandem solar PVC with G–ZnO as TCE on micromorph thin-film has shown efficiency of 14.7% (Table 2). Simulations demonstrate that proposed G-ZnOmsPVC with a larger band gap and buffer layers at p/i interfaces craves the power conversion efficiency more

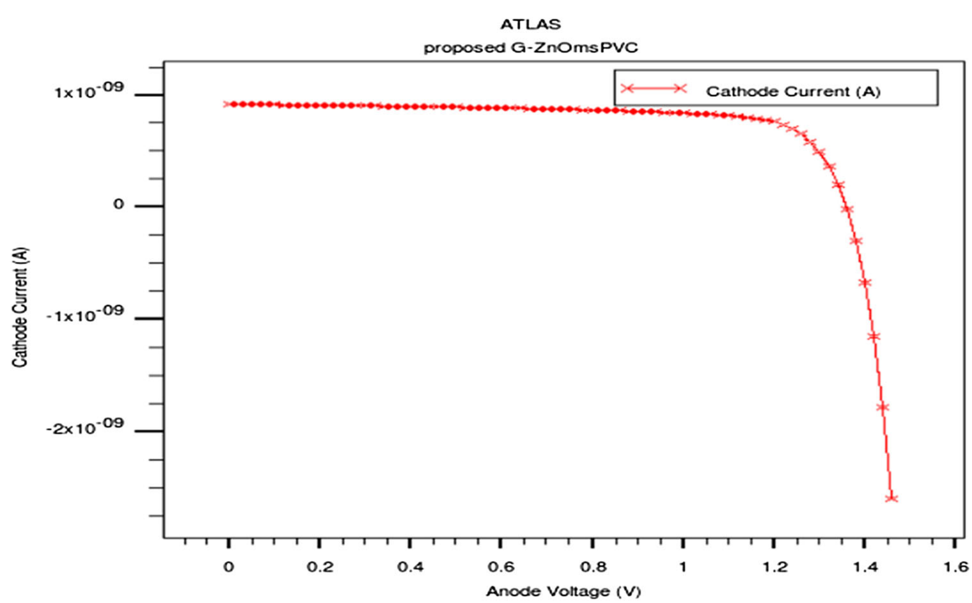

Fig. 12 I–V characterization of proposed G-ZnOmsPVC solar cell

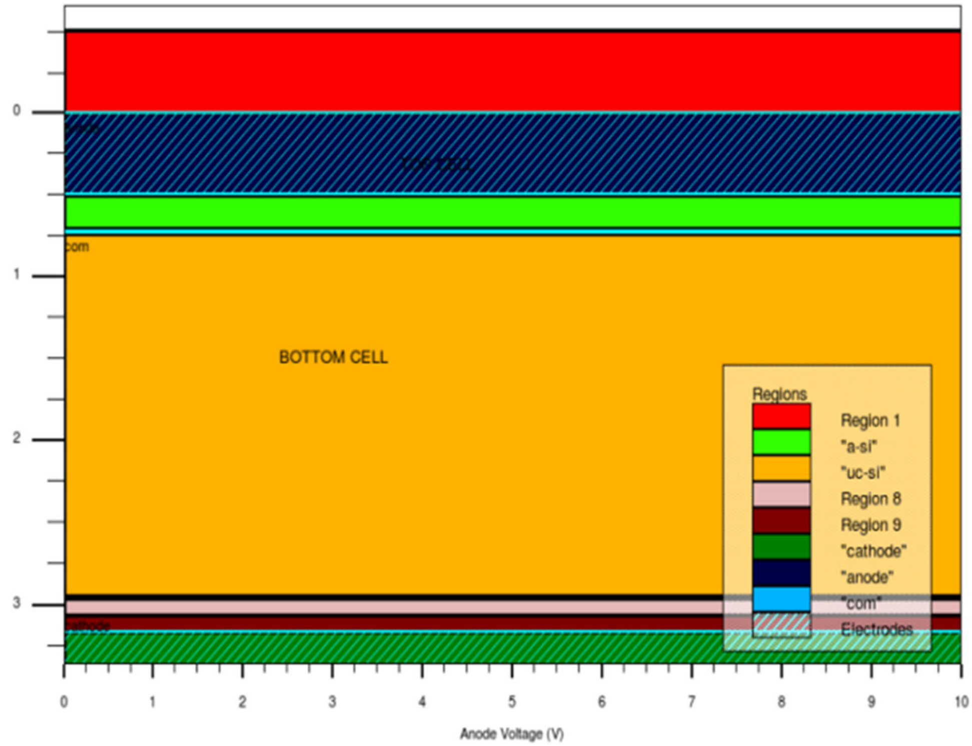

Fig. 13 Region wise specification of proposed G-ZnOmsPVC solar cell

Table 2 Comparison of new proposed model of solar PVC structures with spectrum AM 1.5G

Solar cells	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	η (%)
Bai et al. [28]	0.555	25.72	70.1	10.5
Meillaud et al. [29]	1.38	11.9	73.7	12.1
Fang et al. [30]	1.391	13.69	77.7	13.65
This model	1.45	14.45	78.3	14.7

Table 3 Output parameters obtained by the simulation

Performance metrics	Graphene (a-Si) thin film solar PVC	G-ZnOmsPVC
Open circuit voltage, V_{oc}	1.287	1.45
Short circuit current, J_{sc} (mA/cm^2)	10.19	14.45
Fill factor, FF	71.843	78.3
Efficiency, η (%)	9.86	14.7

effectively in comparison to micromorph solar PVC with so far shown in Table 2.

The incorporation of top cell a-Si:H and bottom cell μc-Si:H allows the enhancement of the open-circuit voltage which helps in increasing the efficiency of the cell. Within the structure ZnO/Al is deposited as a superstrate. ZnO and Ag are used as back reflectors having realistic reflectance. Table 3 shows results of graphene as TCE for a-Si solar PVC. The results are comparable with ITO as TCE solar PVC. Use of low cost graphene as TCE increases the life span of cell and hence is shown as a replacement of costly ITO.

7 Conclusion

With the growing technology there is a great advancement in the thin film solar cells which is widely preferable than conventional solar cells because of their flexibility and less cost. Multiple junction solar PVC are well recommended due to the good achieved efficiency with the help of various junctions but light induced degradation effects its lifetime. The paper proposes a a-Si:H/μc-Si:H thin film tandem cell with the incorporation of G–ZnO as TCE which shows the enhanced absorption spectrum and better photon management making it electrically and optically improved. The proposed G-ZnOmsPVC proves to be a perfect combination in terms of band gap for thin film tandem configuration and is able to reduce the degradation of induced light with better efficiency. The power conversion efficiency has been optimised by varying the thicknesses of the G–ZnO layer which shows increase in 41.8% in J_{sc} with significant enhancement in conversion efficiency up to 49.08%.

References

1. Damiano A, Gatto G, Marongiu I, Porru M, Serpi A (2014) Real-time control strategy of energy storage systems for renewable energy sources exploitation. IEEE Trans Sustain Energy 5(2):567–576
2. Bagher AM, Vahid MMA, Mohsen M (2015) Types of Solar Cells and Applications. Am J Opt Photonics 3:94–113
3. Wurfel Uli, Cuevas Andres, Wurfel Peter (2015) Charge carrier separation in solar cells. IEEE J Photovolt 5:461–469
4. Bondja CN, Geng Z, Granzner R, Pezoldt J, Schwierz F (2016) Simulation of 50-nm gate graphene nanoribbon transistors. Electronics. doi:10.3390/electronics5010003
5. Vaianella F, Rosolen G, Maes B (2015) Graphene as a transparent electrode for amorphous silicon-based solar cells. J Appl Phys 117(24):243102
6. Ke Q, Wang J (2016) Graphene based materials for supercapacitor electrodes—a review. J Materiomics 2(1):37–54
7. Smith DD, Cousins P, Westerberg S, De Jesus-Tabajonda R, Aniero G, Shen Y-C (2014) Toward the practical limits of silicon solar cells. In: Proc. 40th IEEE photovoltaic spec. conf. pp 1465–1469
8. Mohammed Ikbal Kabir, Seyed A. Shahahmadi, Victor Lim, Saleem Zaidi, Kamaruzzaman Sopian, and Nowshad Amin (2012) Amorphous Silicon Single-Junction Thin-Film Solar Cell Exceeding 10% Efficiency by Design Optimization, International Journal of Photoenergy, vol. 2012. doi:10.1155/2012/460919
9. You J, Dou L et al (2013) Recent trends in polymer tandem solar cell research. J Prog Polym Sci 38(12):1909–1928
10. Chowdhary TH, Islam A et al (2016) Prospects of graphene as a potential carrier-transport model in third generation solar cells, vol 16. The Chemical Society of Japan and Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, pp 614–632
11. Youngseok L, Vinh AD, Iftiquar SM, Sangho K, Junsin Y (2016) Current transport studies of amorphous n–p junctions and its application in a-Si:H/HITtype tandem cells. J Prog Photovolt 24:52–58
12. Saranya M, Ramachandran R, Wang F (2016) Graphene–zinc oxide (G-ZnO) nanocomposite for electrochemical supercapacitor application. Adv Mater Devices 1(4):454–460
13. Kabir MI, Ibrahim Z, Sopian K (2010) Effect of structural variations in amorphous silicon based single and multi-junction solar cells from numerical analysis. J Solar Energy Mater Solar Cells 94(9):1542–1545
14. Kuang Y, Liu Y, Ma Y et al (2015) Modeling and Design of Graphene GaAs Junction Solar Cell. Adv Conden Matt Phys 2015. doi:10.1155/2015/326384
15. Lu MN, Chang CY, Wei TC, Lin JY (2016) Recent development of graphene-based cathode materials for dye-sensitized solar cells. J Nanomaterials 2016. doi:10.1155/2016/4742724
16. Castens L, Bailat J, Benagli S et al (2009) Advanced light management in micromorph solar cells. In: Inorganic nanostructured photovoltaics symposium B. pp 35–39
17. Meillaud F, Battaglia C et al (2011) Latest developments of high efficiency micromorph tandem silicon solar cells implementing innovative substrate materials and improved cell design. In: IEEE photovoltaic specialist conference (PVSC). doi:10.1109/PVSC.2011.6185923
18. Singh E, Nalwa HS (2015) Graphene based bulk heterojunction solar cells: a review. J Nanosci Nanotechnol 9:6237–6278
19. Taguchi M, Yano A, Tohoda S, Matsuyama K, Nakamura Y, Nishiwaki T, Fujita K, Maruyama E (2014) 24.7% record efficiency HIT solar cell on thin silicon wafer. IEEE J Photovolt 4:96–99
20. Singh S, Singh A, Kaur N (2016) Efficiency investigations of organic/inorganic hybrid ZnO nanoparticles based dye-sensitized solar cells. J Mater 2016. doi:10.1155/2016/9081346
21. Fujimoto Y (2015) Formation, energetics, and electronic properties of graphene monolayer and bilayer doped with heteroatoms. Adv Condens Matter Phys 2015. doi:10.1155/2015/571490 (**Article ID 571490**)
22. Atlas User Manual Guide (2012)
23. Zeman M, Krc J (2008) Optical and electrical modelling of thin film solar cells. J Mater Res 23(4):889–898
24. Pathak MJM, Girotra K, Harrison SJ, Pearce JM (2012) The effect of hybrid photovoltaic thermal device operating conditions on intrinsic layer thickness optimization of hydrogenated amorphous silicon solar cells. Solar Energy 86:2673–2677
25. Peplow M (2013) Graphene: the quest for supercarbon. Nature 503(7476):327–329
26. Kaplan D, Swaminathan V, Recine G, Balu R, Karna S (2013) Bandgap tuning of mono-and bilayer graphene doped with group IV elements. J Appl Phys 113(18):183701
27. Faryad M, Lakhtakia A (2013) Enhancement of light absorption efficiency of amorphous silicon thin-film tandem solar cell due to multiple surface-plasmon-polariton waves in the near-infrared spectral regime. Opt Eng 52(8):087106
28. Bai L, Liu B et al (2015) Effect of I/N interface on the performance of superstrate hydrogenated microcrystalline silicon solar cells. J Solar Energy Mater Solar Cells 140:204–208
29. Meillaud F, Billet A et al (2012) Latest developments of high-efficiency micromorph tandem silicon solar cells implementing innovative substrate materials and improved cell design. IEEE J Photovolt 2(3):236–240
30. Fang J, Bai L et al (2016) High-efficiency micromorph solar cell with light management in tunnel recombination junction. J Solar Energy Mater Solar Cells 155:469–473
31. Tavakoli MM, Tavakoli R, Hasanzadeh S, Mirfasih MH (2016) Interface engineering of perovskite solar cell using a reduced-graphene scaffold. J Phys Chem C 120(35):19531–19536
32. Avrutin V et al. (2014) Amorphous and micromorph Si solar cells: current status and outlook. Turk J Phys 38:526–542. doi:10.3906/fiz-1406-14
33. Jeng-Yu L et al. (2015) Molybdenum disulfide/reduced graphene oxide–carbon nanotube hybrids as efficient catalytic materials in dye-sensitized solar cells. J Chem Electro Chem. doi:10.1002/celc.201402423
34. Hafezi R et al. (2015) Material and solar cell research in high efficiency micromorph tandem solar cell. J of Ciência eNatura 37(2):434–440
35. Chander S, Purohit A, Nehra A, Nehra SP, Dhaka MS (2015) A study on spectral response and external quantum efficiency of mono-crystalline silicon solar cell. Int J Renew Ener Res 5(1):41–44
36. Ray SK et al. (2015) Design and modelling of GAAS/ INGAP/ INGAAS/ GE III–V triple junction solar cell. Inter J Elect Electron Eng 7(1):146–151