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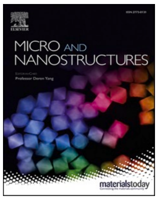

Effect and optimization of ZnO layer on the performance of GaInP/GaAs tandem solar cell

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ABSTRACT

Two-dimentionnal Atlas SILVACO-TCAD® device simulator is used to simulate the performances of dual-junction (2J) GaInP/GaAs tandem solar cell under AM1.5G illumination spectrum. The structure of GaInP/GaAs tandem solar cell consists of the combination of two single-junctions based on GaInP top-cell and GaAs bottom-cell. The performance of GaInP/GaAs tandem solar cell is studied using ZnO intermediate layer as a transparent conducting oxide (TCO) between the bottom and top cells to connect them in serial structure. An undoped ZnO front layer is used as an anti-reflective (AR) layer in front side of GaInP top-cell to enhance the conversion efficiency. Without ZnO front layer, a conversion efficiency of 25.29% has been achieved with 0.95 μm base layer thickness of GaInP top-cell and a current-matching density for both cells was Jsc = 11.30 mA/cm2. Optimization resulted in record efficiency of 30.82% in GaInP/GaAs tandem solar cell by introducing ZnO front layer with 0.7 μm base layer thickness of GaInP top-cell with a current-matching density of 13.66 mA/cm^2 and an open circuit voltage of 2.51 V. The GaInP/GaAs tandem solar cell in current study exhibit an improvement in conversion efficiency using anti-reflective ZnO front layer. This results are a promising step to fabricate an efficient III-V multi-junctions solar cells.

1. Introduction

Transparent conducting oxides (TCOs) are widely used in opto-electrical field such as solar cells, opto-electrical interfaces and electronic circuits [1]. ZnO thin films are promising alternative to the commonly used indium tin oxide (ITO) due to their cost effectiveness, non-toxicity and durablity against hydrogen plasma [1]. The ZnO exhibit good transparency in visible region due to its wide band gap of 3.3 eV [2]. For solar cells, ZnO thin film is being used as an intermediate layer for the transparent and conductive connection between two cells, like dual-junction III-V/Si solar cell [3] and a-Si:H/μc-Si:H tandem solar cell [4]. Moreover, the ZnO is amongst materials being used as anti-reflection coatings (ARCs) owing to its low refractive index (∼1.65) [5]. The role of anti-reflection coating is to reduce the photons reflection from the surface of cell in order to improve the photo-carrier generation rate

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and cell efficiency [6].

The dual-junction solar cell composed of two sub-cells would achieve a better conversion efficiencies. High efficiencies of about 25.28, 25.15 and 25.14 have been achieved using InGaP/InGaP, AlGaAs/AlGaAs and GaAs/GaAs tunnel junctions, respectively, without ARC [7]. Makableh et *al.* reported that ZnO anti-reflection coating enhances the performance of GaAs solar cell [5]. The dual-junction GaInP/GaAs solar cell proved with ZnS/MgF_2 double-layer anti-reflection coating an efficiencies of 27.30% and 28.57% experimentally and theoretically, respectively, using GaAs/GaAs tunnel junction [8] and also 30.28% experimentally with InGaP/InGaP tunnel junction [9] and about 29.83% with GaAs/GaAs tunnel junction using the simulator SCAPS-1D [10]. An experimental study using Te doping in the GaAs tunnel junction of GaInP/GaAs tandem solar cells showed a higher efficiency of 28.06% [11]. Özen et *al.* [12] reported the fabrication and characterization of GaInP/GaAs solar cell structure with AlGaAs tunnel junction. They found that an efficiency of 13.52% was achieved using AlGaAs tunnel junction. They attributed the high tunneling effect of AlGaAs material to its good physical characteristics. These physical characteristics are include the good lattice match, the lower resistivity that facilitate the flow of current, the higher band gap compared to the band gap of the sub layer, and the transparency to the photons that are absorbed in the bottom cell.

In this work, we will investigate in more detail the effect of base layer thickness of GaInP top-cell on the performance of GaInP top-cell, GaAs bottom-cell and 2J GaInP/GaAs tandem solar cell and look at the effect of the having a ZnO intermediate layer in the structure. The intermediate layer has been inserted between the top and bottom cells to connect them in serial structure. The study has been carried out by 2D simulation using Atlas SILVACO tool [13] to evaluate the performance improvement of 2J GaInP/GaAs tandem solar cell with and without anti-reflective ZnO front layer.

2. GaInP/GaAs tandem solar cell structure

The simulated tandem solar cell structure, as shown in Fig. 1 is a combination of two stacked single n-emitter/p-base sub-cells with integrated absorption spectra. As shown in Fig. 1(a), the top cell is a GaInP junction with a high bandgap of 1.9 eV and the bottom cell is a GaAs junction with a low bandgap of 1.424 eV. These two sub-cells are connected optically and electrically by Al-doped ZnO (AZO) as an intermediate layer with a thickness of 300 nm [14,15] (see Fig. 1).

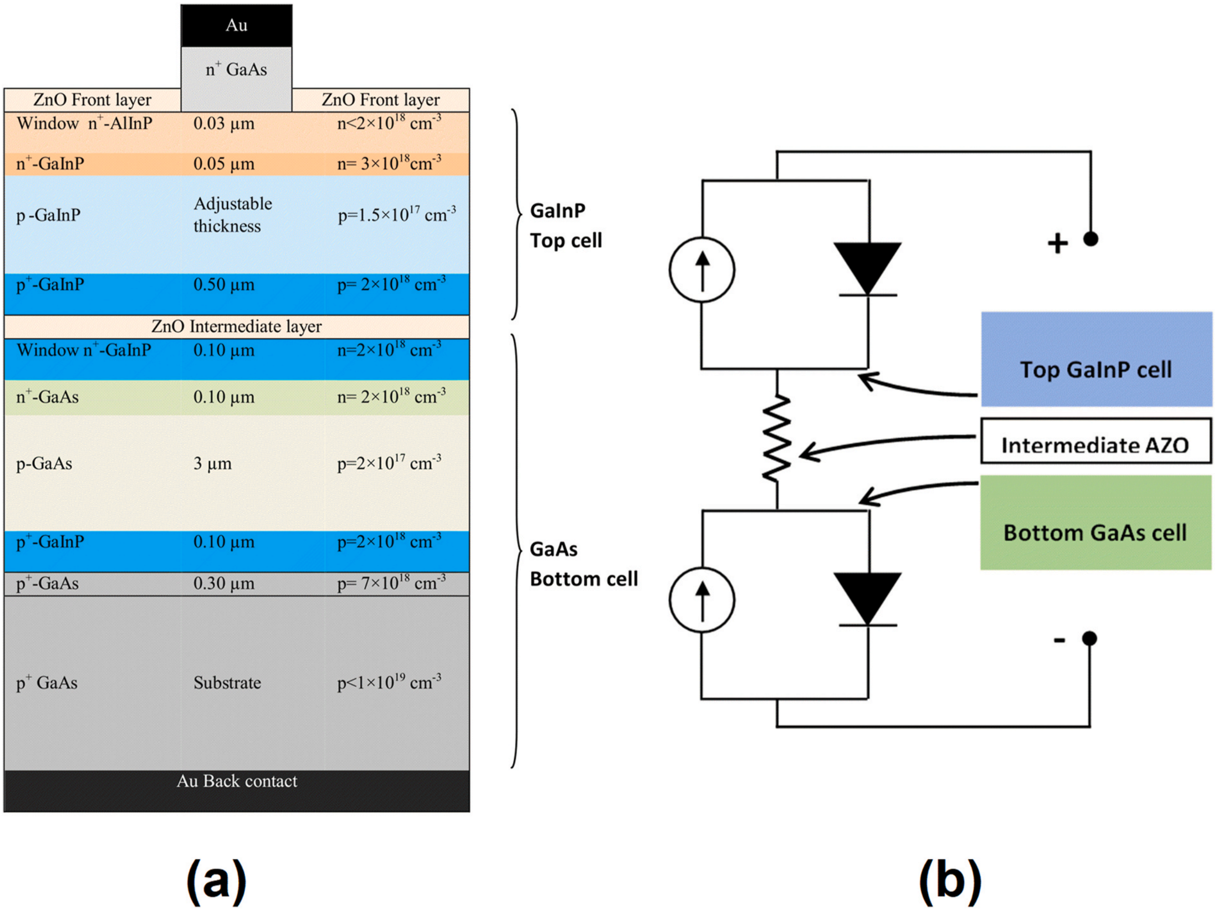

Fig. 1. (a) Structure and (b) equivalent circuit of the proposed GaInP/GaAs tandem solar cell.

At first sight and without ZnO intermediate layer, the stacking GaInP and GaAs junctions on top of each other without any interconnection would lead to p/n diode between the top sub-cell and the bottom sub-cell and this reverse diode would block the current flow. In other words, without an interconnection, the p^+-GaInP region of the top cell would be directly connected with the n^+-GaInP region of the bottom cell. Hence, a direct p^+-GaInP/n^+-GaInP junction with opposite direction to the others would appear between the top GaInP cell and the bottom GaAs cell that it would block the current flow. Thus, an interconnection between the top cell and bottom cell needs to be implemented. This interconnection consists of a recombination layer, which takes an essential role in determining the performance efficiency in series-connected tandem devices. It should have an ohmic or low-resistive electrical connection which will allow arising low barriers for carrier (hole and electron) extraction and a low optical absorption in visible and infrared regions. The Al-doped ZnO (AZO) material is a highly doped ($N_d = 10^{19}$ cm^{-3}) transparent conducting metal oxide (TCO) with a wide bandgap (3.3 eV), a low electrical resistance and low-loss optically connection layer [16]. By taking the AZO TCO as an intermediate layer, the electrons will be capable to tunnel through it [17]. In this case, the 2J cell will have a total current limited by the sub-cell with minimum short-circuit current (J_{SC}), and a total voltage equal to the sum of the open-circuit voltages (V_{OC}) of the top and bottom cells. Therefore, the scheme shown in Fig. 1(b) represents the equivalent circuit model for the simulated 2J tandem solar cell by considering the interconnection AZO layer as a series resistance to connect the 2J GaInP/GaAs cells and to insert a good tunneling layer [17,18].

It is obvious that the top sub-cell facing the sun absorbs all the photons with energy at and above its bandgap (1.9 eV) and transmits the photons with low energy to the bottom sub-cell. The transmitted photons before entering the bottom cell, they will easily penetrate the transparent intermediate ZnO layer, which has a bandgap of 3.3 eV with almost no loss whether by absorption or reflection. As a result, this intermediate ZnO layer provides high transparency satisfying the optical requirement of tandem solar cell.

For the modeling calculations and the performance analysis of 2J GaInP/GaAs tandem solar cell structure (Fig. 1(a)), SILVACO Atlas simulator was used. The optoelectronic properties of the structure were analyzed numerically by estimating the carrier transport in two dimensions, recombination profile and steady state band diagram based on the Poisson and the hole/electron continuity equations. Recombination currents were calculated by employing the Shockley–Read–Hall (SRH) model for bulk defects in the cells [13]. The radiation AM 1.5 G with a power density of 100 mW/cm^2 used as an illumination source at 300 K. For electrons and holes, surface recombination velocities were set as 10^7 cm/s. For optimization, all the parameters of GaAs layer were kept constant. The reflection of the ZnO intermediate layer does not take into account in the model. The light absorption coefficient for GaInP and GaAs layers have been incorporated from the values incorporated in SILVACO database [13]. Table 1 shows the values of the layers parameters used in the current simulation [8,9].

The effect of geometrical properties of top-cell on the performance of 2J GaInP/GaAs tandem solar cell has been studied using (2D) SILVACO-Atlas simulator and the electrical parameters were determined from the Current density-Voltage carateristics (*J*-*V* curves). In the simulation model, contacts, material properties and choice of physical models were defined and mathematical methods used according to Silvaco User's Manual [13]. The 2J GaInP/GaAs tandem solar cell is studied with the presence and the absence of an undoped ZnO front layer of GaInP top-cell with a thickness of 100 nm [15]. For other different layers the thickness and the doping concentrations are shown inside the structure (Fig. 1(a)).

3. Results and discussions

3.1. *Performance analysis of 2J GaInP/GaAs tandem solar cell without ZnO front layer*

The simulated J-V characteristics for tandem solar cell, shown in Fig. 1(a) without ZnO front layer and with a base layer thickness of GaInP top-cell about 0.3 μm, are presented in Fig. 2. As shown, two important points were noticed, as the sub-cells are connected in serial structure using ZnO intermediate layer, it gives an open-circuit voltage (V_{OC}) exactly equal to the combined value of V_{OC} of the top and bottom cells (the sum), the short-circuit current density (J_{sc}) of the tandem solar cell is limited by the lower short-circuit current density of both sub-cells.

In this section and without ZnO front layer, the base layer thickness of GaInP top-cell, *d*(GaInP), was varied from 0.6 to 1.3 μm. The disparity in short-circuit current densities as a function of *d*(GaInP) is shown in Fig. 3. Higher base layer thickness of GaInP top-cell impacted the short-circuit current densities for both sub-cells. A higher *d*(GaInP) reduces the light emitting to penetrate the top-cell part, which basically increases J_{SC} in GaInP top-cell. However, higher value of *d*(GaInP) corresponds to the decrease in carrier generation in the absorber bulk of bottom-cell (shadowing effect) resulted in reduction of short circuit current density. The optimum value obtained of *d*(GaInP) was 0.95 μm gives an ideal current density. The current-matching point obtained in this case was 11.30 mA/cm^2.

Table 1
Material parameters used in the simulation.

Parameters	AlInP	GaInP	GaAs	ZnO
Band gap E_g (eV)	2.4	1.9	1.424	3.3
Electron affinity χ_e (eV)	4.2	4.09	4.07	4
Relative permittivity ε_r (Fcm^{-1})	11.7	11.08	12.9	9
Electron mobility μ_n (cm^2/V s)	2291	1945	8500	50
Hole mobility μ_p (cm^2/V s)	142	141	400	5
Conduction band effective density of states N_C (cm^{-3})	1.08×10^{20}	6.55×10^{17}	4.7×10^{17}	2.2×10^{18}
Conduction band effective density of states N_V (cm^{-3})	1.28×10^{19}	1.5×10^{19}	9×10^{18}	1.8×10^{19}

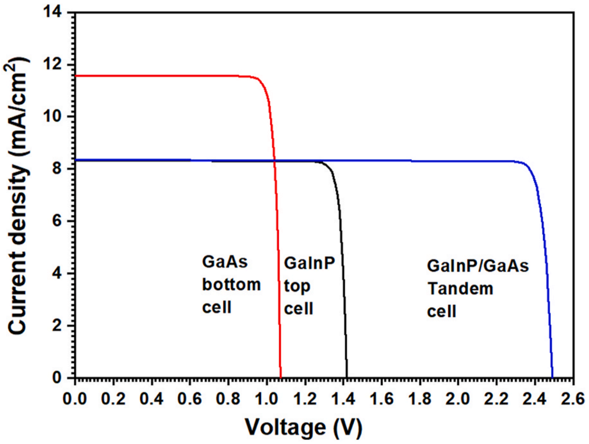

Fig. 2. J-V curves of top-cell, bottom-cell and of the dual-junction InGaP/GaAs tandem solar cell without ZnO front layer and with 0.4 μm base layer thickness of GaInP top-cell.

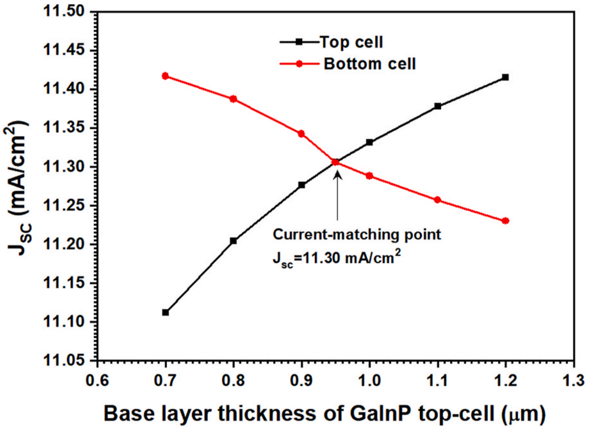

Fig. 3. Short-circuit current densities of GaInP top-cell and GaAs bottom-cell as a function of the base thickness of InGaP top-cell without ZnO front layer.

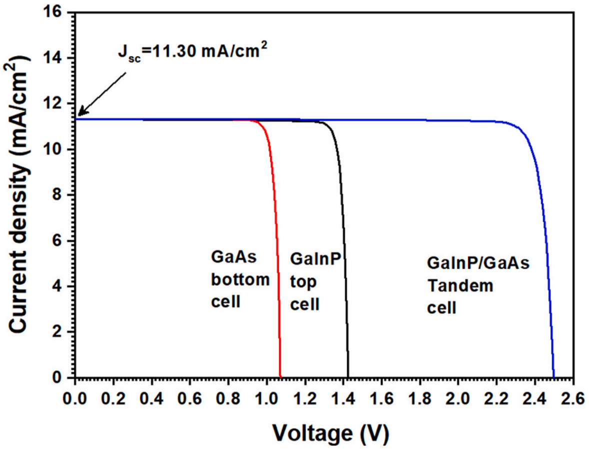

Fig. 4. J-V curves of top-cell, bottom-cell and of the dual-junction InGaP/GaAs tandem solar cell without ZnO front layer and with 0.95 μm base layer thickness of GaInP top-cell.

A prominent rise in J_{SC} up to unendurable limit of d(GaInP) improve the efficiency up to 25.29%. These results are in good agreement with the simulation values for InGaP/GaAs dual-junction solar cells using InGaP/InGaP as tunnel junction [7].

Using 0.95 μm base layer thick of GaInP top-cell, the simulated current density-voltage curves are shown in Fig. 4. The calculated electrical parameters of GaInP top-cell, GaAs bottom-cell and GaInP/GaAs tandem solar cell without ZnO front layer are summarised in Table 2.

3.2. Effect of ZnO front layer on the performance of 2J InGaP/GaAs tandem solar cell

In the previous InGaP/GaAs tandem structure, an undoped ZnO front layer is introduced as an anti-reflective (AR) layer in the front side of GaInP top-cell with a thickness of 100 nm [15]. Fig. 5 shows the *J-V* characteristics of 2J InGaP/GaAs tandem solar cell with and without ZnO front layer. The presence of ZnO front layer can gives a better short-circuit current density, $J_{SC} = 13.66$ mA/cm^2 (case A) instead of 11.30 mA/cm^2 in case of GaInP/GaAs tandem solar cells without ZnO front layer (case B). This improvement in J_{sc} proves that the presence of ZnO anti-reflection layer improves the reflective properties of the surface of the top cell. The phenomenon of the enhancement in *J-V* characteristics was also observed experimentally using ZnO layer as an anti-reflection coating (ARC) on the GaAs solar cell in Ref. [5] and as a nanowires in case of GaInP/GaAs/Ge triple-junctions solar cell [17].

To estimate the optimum base layer thickness of GaInP top-cell for highly efficient GaInP/GaAs tandem solar cells, the base layer d (GaInP) was varied between 0.3 and 1.1 μm by introducing ZnO front layer. Fig. 6 shows the variation of short-circuit current density as a function of d(GaInP) for both sub-cells. The results indicate that the J_{sct} for GaInP top-cell increased with increasing the base layer thickness, contrariwise the J_{scb} for GaAs bottom-cell decreased strongly when d(GaInP) raises. The current-matching point obtained in this case was 13.66 mA/cm^2 with an optimum thickness of base layer of GaInP top-cell equal to 0.7 μm.

The simulated current density-voltage (*J-V*) characteristics for GaInP top-cell, GaAs bottom-cell and InGaP/GaAs tandem cell with ZnO front layer are shown in Fig. 7. The open-circuit voltage (V_{OC}) of the GaInP/GaAs tandem cell is around 2.51 V and the other photovoltaic parameters are summerised in Table 3.

The effect of various tunnel junctions (GaAs/GaAs, AlGaAs/AlGaAs, InGaP/GaAs and InGaP/InGaP) on the performance of 2J InGaP/GaAs tandem solar cell has been simulated using Silvaco-Atlas 2D simulator [7,19], the obtained results showing that the InGaP/InGaP tunnel diode gives a higher conversion efficiency for the bottom cell compared to other tunnel junctions [7,19]. This improvement has been explained in Ref. [7] by the higher EQE of the bottom-cell due to the wide band-gap energy of InGaP material. F. Djaafar et *al.* [19] reported that the InGaP tunnel junction will allow photons to pass through as well as pass current with minimal voltage loss.

3.3. Electrical parameters of 2J GaInP/GaAs tandem solar cell with ZnO front layer

In this section, we examine the photovoltaic parameters of GaInP/GaAs tandem cell using ZnO front layer under AM1.5G illumination as a function of d(GaInP). The *J-V* characteristics and their photovoltaic parameters: Conversion efficiency (η), open-circuit voltage (V_{OC}), short-circuit current density (J_{SC}) and fill-factor (*FF*) have been calculated and presented as a function of d(GaInP) in Fig. 8(a–d). The short-circuit current density (J_{SC}) is given in Fig. 8(a). For a thick base layer of GaInP top-cell, the short-circuit current density of GaAs bottom-cell is observed to be lower than that for top-cell ($J_{scb} < J_{sct}$). The J_{scb} increases from 13.48 to 13.66 mA/cm^2 as the thickness of base layer reduces from 0.95 to 0.7 μm. The thickness of base layer of GaInP top-cell reduces to the current matching point when $J_{sct} = J_{scb} = 13.66$ mA/cm^2. The optimum base layer thickness is 0.7 μm. With decreasing the base layer thickness below 0.7 μm, the J_{sct} decreases while the J_{scb} increases, with $J_{scb} > J_{sct}$. This observation would result from low absorption at the top-cell.

The open-circuit voltage V_{OC} remains almost constant when the thickness of base layer of top-cell increases (Fig. 8(b)). The fill factor *FF* of GaInP/GaAs tandem-cell presents a reverse behavior related to short-circuit current density variation. The *FF* has a minimum value of 89.91% at the optimum base layer thickness of 0.7 μm (Fig. 8(c)). The conversion efficiency η shows a similar behavior related to short-circuit current density when the thickness of base layer of GaInP top-cell decreases (Fig. 8(d)). It approaches a maximum value of 30.82% at an optimum base layer thickness of GaInP top-cell equal to 0.7 μm.

Table 4 summarizes the obtained photovoltaic parameters of investigated 2J InGaP/GaAs tandem solar cell and compares them with those previously obtained from experimental [8,9] and simulation [20,21] studies.

The results shown in Table 4 indicated that the simulated 2J InGaP/GaAs tandem cell achieved an improvement in efficiency up to 30.82% compared to recorded efficiencies of about 30.40% in Ref. [20] and 29.62% in Ref. [21]. In addition, this efficiency improvement is in good agreement with the experimental results using InGaP/InGaP tunnel junction [9] and better than those obtained by using GaAs/GaAs tunnel junction [8] with ZnS/MgF$_2$ double-layer antireflection coating.

Table 2
Photovoltaic parameters of InGaP top-cell, GaAs bottom-cell and InGaP/GaAs tandem solar cell without ZnO front layer.

	J_{SC} (mA/cm^2)	V_{OC} (V)	P_{m} (mW/cm^2)	*FF* (%)	η (%)
InGaP top-cell	11.30	1.424	14.53	90.26	14.53
GaAs bottom-cell	11.30	1.073	10.77	88.85	10.76
InGaP/GaAs tandem solar cell	11.30	2.497	25.30	89.63	25.29

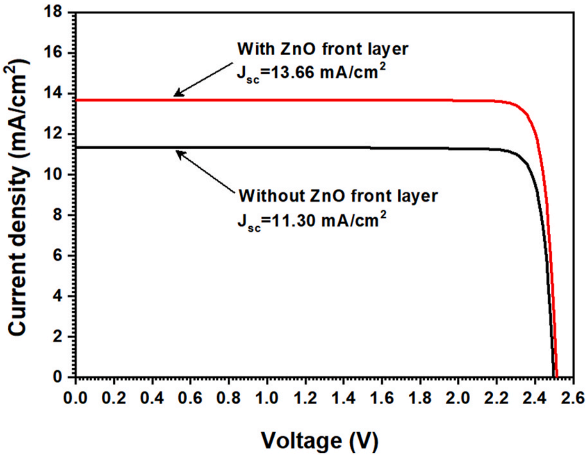

Fig. 5. J-V characteristics of the 2J InGaP/GaAs solar cell with and without ZnO front layer.

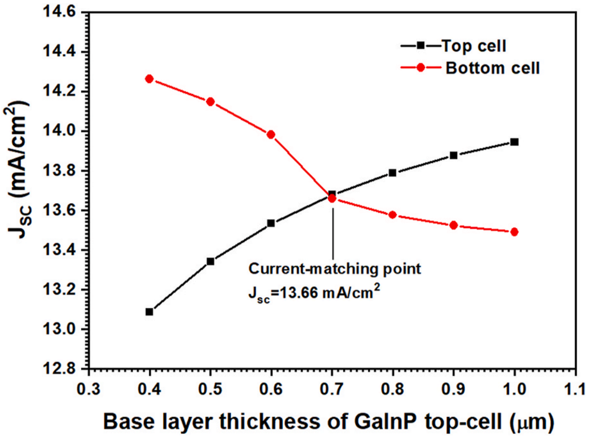

Fig. 6. Short-circuit current densities of GaInP top-cell and GaAs bottom-cell as a function of the base layer thickness of GaInP top-cell with ZnO front layer.

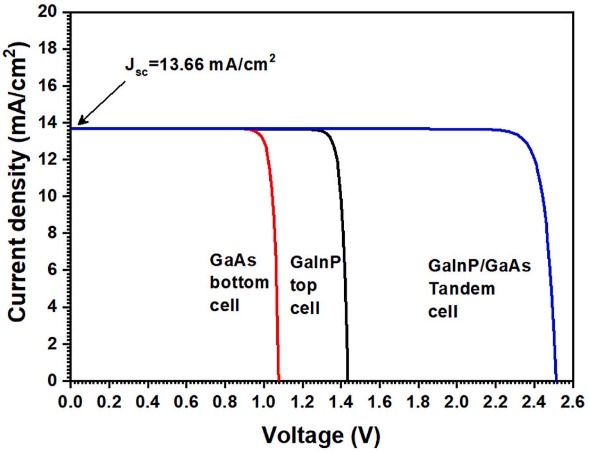

Fig. 7. J-V curves of top-cell, bottom-cell and of the dual-junction InGaP/GaAs tandem solar cell with ZnO front layer and with 0.7 μm base layer thickness of GaInP top-cell.

Table 3
Photovoltaic parameters of top, bottom and tandem solar cells with ZnO front layer.

	J_{SC} (mA/cm^2)	V_{OC}(V)	P_m(mW/cm^2)	FF (%)	η (%)
InGaP top-cell	13.66	1.433	17.76	90.61	17.75
GaAs bottom-cell	13.66	1.078	13.08	88.88	13.07
InGaP/GaAs tandem-cell	13.66	2.511	30.84	89.91	30.82

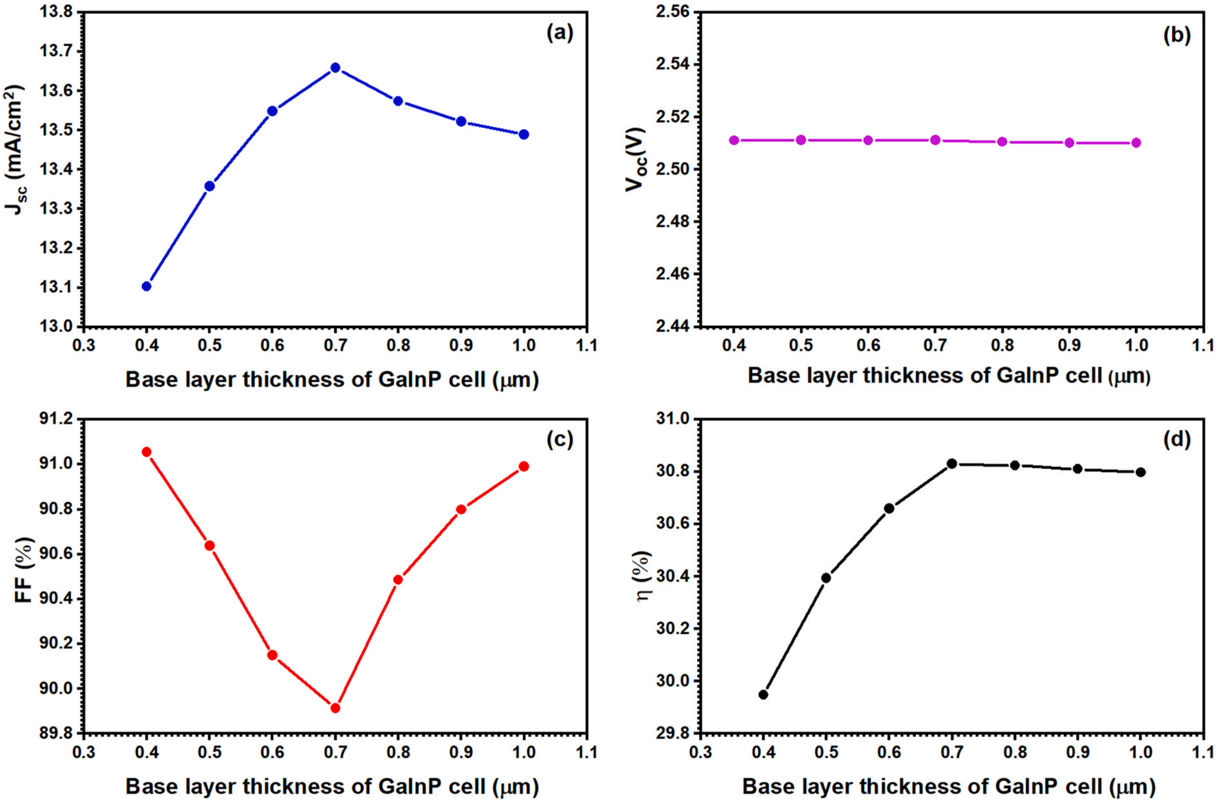

Fig. 8. Photovoltaic parameters of the GaInP/GaAs tandem solar cell with ZnO front layer as a function of the base layer thickness of InGaP top-cell.

Table 4
Comparison between the photovoltaic parameters obtained in our work with those presented in the literature of 2J InGaP/GaAs tandem solar cells.

	J_{sc} (mA/cm^2)	V_{oc}(V)	FF(%)	η(%)	
InGaP/GaAs tandem-cell, this work	13.66	2.51	89.91	30.82	Simulation
InGaP/GaAs tandem-cell, by T. Takamoto et *al.* [9]	14.22	2.48	85.60	30.28	Expirement
InGaP/GaAs tandem-cell, by T. Takamoto et *al.* [8]	13.16	2.41	85.80	27.30	Expirement
InGaP/GaAs tandem-cell, by G. S. Sahoo et *al.* [20]	13.97	2.45	88.55	30.40	Simulation
InGaP/GaAs tandem-cell, by N. Jain et *al.* [21]	14.18	2.37	88.22	29.62	Simulation

4. Conclusion

The performance of GaInP top-cell, GaAs bottom-cell and GaInP/GaAs tandem cell, as a function of base layer thickness of GaInP top-cell have been studied by using Atlas SILVACO-TCAD software. The J-V characteristics and the photovoltaic parameters have been investigated in order to evaluate the conversion efficiency of GaInP/GaAs tandem cell with and without ZnO front layer. The two sub-cells are connected by ZnO intermediate layer used as a transparent conducting oxide. Without ZnO front layer, a conversion efficiency of 25.29% has been observed, which is in good agreement with reported simulation results with different tunnel diodes. The current-matching point was obtained at 11.33 mA/cm^2 for all cells with 0.95 μm base layer thickness of GaInP top-cell. The inclusion of ZnO front layer resulted an improved efficiency up to 30.82%. This optimum solar cell efficiency is observed for 0.7 μm as an optimum base layer thickness of GaInP top-cell. The short-circuit current densities for all cells are equal to 13.66 mA/cm^2 with current-matching condition. The improvement in the conversion efficiency to 30.82% is in good agreement with the experimental results using the

InGaP/InGaP tunnel junction. From these results, we suggest the use of ZnO front layer as an antireflective layer and ZnO intermediate layer between GaInP top-cell and GaAs bottom-cell to accomplish highly efficient GaInP/GaAs tandem solar cells with enhanced short-circuit current density.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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