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Improved Theoretical Conversion Efficiency of a Dual Junction GaInP/Si Mechanically Stacked Photovoltaic Cell

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***Abstract* -** Dual junction tandem solar cells can utilize the solar spectrum photons with a broader range of energies as compared to the conventional single junction solar cells; thereby demonstrating higher conversion efficiency. This paper deals with the numerical modeling of a dual junction GaInP/Si based multijunction tandem photovoltaic cell. The semi empirical modeling approach was used for simulation which produced a theoretical one sun conversion efficiency of over 30% for the proposed four terminal configuration.

***Keywords* -** ARC, Open Circuit Voltage, PC1D, Short Circuit Current, Tandem cell, TCO

I. INTRODUCTION

Multijunction solar cells are more sensitive to solar spectrum than single junction solar cells [1-2]. Single junction silicon based solar cells have reached their peak conversion efficiency limits in the field of photovoltaics [3]. However, stacking a silicon solar cell with a higher bandgap material solar cell enables theoretical one sun conversion efficiencies exceeding the 30% limit. A larger bandgap material on the top absorbs photons with higher frequencies ensuring reduction in the efficiency losses associated with the thermalisation process. The materials most suited for the development of high efficiency multijunction solar cells are the III-V compound semiconductors, where the lattice matching condition can be managed. Additionally, silicon as a substrate has the advantages of being relatively cheap and abundant as well as having good radiation resistance [4-5].

Mostly tandem cells use series connection of subcells resulting in two terminal devices. Boundary condition associated with two terminal configuration requires that the current in both the subcells remains equal. For the power output to reach the maximum under these conditions exact current matching is required. This can be achieved by adjusting the thickness and doping concentration of different layers. The power deliverable to an external load is strongly. limited by the efficiency of the top cell. In a four terminal configuration however, the operating points of the subcells can be controlled independently ensuring maximum transfer of power. In a four terminal configuration, the maximum power of each subcell is independent of one another, therefore, the electrical matching remains optimal. Four terminal mechanically stacked GaInP/Si cells are connected by an adhesive which allows higher degree of flexibility in terms of circuit wiring [6-8].

II. MODELING

In this paper, semi empirical modeling was used to demonstrate the performance of GaInP/Si dual junction solar cell. The GaInP and silicon sub-cells were simulated independently each at its own maximum power point. Unlike the monolithic multi-junction devices there is no need for the current matching between the sub-cells here as it is a four terminal configuration.

The integration of the GaInP cell with the Si cell reduces the intrinsic limitation associated with the standalone Si cell. Conversion of the short wavelength radiation associated with the solar spectrum can be achieved by the GaInP cell while the conversion of the longer wavelength radiation is taken care of by the Si cell.

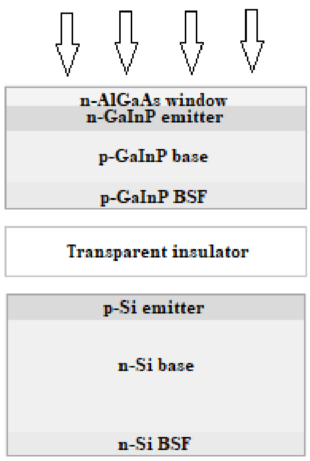

Fig .1. Schematic diagram of the four-terminal photovoltaic cell

Fig. 1 shows the schematic diagram of the dual junction tandem solar cell which comprises a GaInP based top cell of thickness 1.7 µm and a silicon-based bottom cell having thickness of 230 µm. The top cell has an AlGaAs based wide bandgap (2.1eV) window material having variable thickness. Each of the subcells has uniformly doped emitter and base layers of variable thickness and doping concentrations. To generate an electric field barrier for the minority carriers, the top and the bottom subcells have back surface field (BSF) layers of adjustable doping concentration and thickness. The electric field avoids the possibility of surface recombination. However, these adjustments are made keeping the total thickness of the top and the bottom cells constant at 1.7 µm and 230 µm, respectively [9]. In practice, to avoid the inherent optical losses associated with the mechanically stacked solar cells, electrically insulating and optically transparent adhesives are used to bond the cells.

For the sake of simplicity, the structure used for electrical characterization does not incorporate any defects at the interface and the surface or losses related to the tunnel junction (for the two terminal configuration) and the insulation. The operating temperature was chosen to be 25ºC with a device area of 1cm^2. The optimization of the sub-cells was performed under AM1.5G one sun illumination condition having an intensity of 0.1W/cm^2. The modeling and simulations were performed using PC1D simulation software [10], which is a computer program used for modeling crystalline semiconductor devices with emphasis on photovoltaic devices and is used as a simulation tool to understand the operation of solar cells yielding reliable results. The parameters used in the simulation are taken from reference [9]. The GaInP top cell has a ZnS anti-reflection coating on the front side and the Si bottom cell has a TCO coating on the front face (not shown in fig. 1). The ZnS and the TCO coatings on the front side of the cells have been optimised using simulations. The modelling considers a 1.7µm thick GaInP cell and a 230µm thick Si cell with constant light trapping.

III. RESULTS AND DISCUSSION

Historically, AlGaAs/Si dual junction solar cell has achieved 1-sun efficiency exceeding 21% by the epitaxial growth technique [11]. III-V/Si multi-junction solar cells were also demonstrated to achieve efficiencies of over 25% and 30% under 1-sun and 112-suns by means of direct wafer bonding [12-13]. Mechanically stacked GaInP/InGaAs/Si based solar cell has been reported to achieve efficiency of over 27% under 1-sun [14].

Unlike the AlInP window layer, S. Essig, M. A. Steiner, C. Allebé, J.F. Geisz, B. Paviet-Salomon, S. Ward, A. Descoeudres, V. LaSalvia, L. Barraud, N. Badel, A. Faes, J. Levrat, M. Despeisse, C. Ballif, P. Stradins, D.L. Young, “Realization of GaInP/Si dual-junction solar cells with 29.8% one-sun efficiency”, an AlGaAs window layer having a dielectric constant of 10.63 is chosen over the GaInP top cell having a lattice mismatch of only 0.03%. The window layer has a uniform n-type doping concentration of 1x10^{17}atoms/cm^3. The thickness of the window layer is varied to find the optimum value of efficiency.

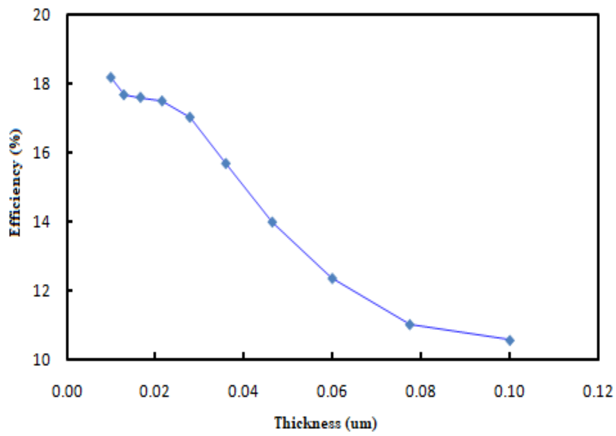

Fig .2. Window layer thickness vs. efficiency

The result of the simulation (Fig. 2) indicates that the efficiency is at a maximum value of 18.17% when the thickness of the window layer is at 0.01µm.

A study to determine the influence of the thickness of the ZnS anti-reflection coating on the fraction of photon current absorbed and reflected for the GaInP cell was performed. The incident light passes through the ZnS anti-reflective coating (refractive index=3.805-2.252) and the AlGaAs window layer (refractive index=1.368-3.124) before reaching the GaInP substrate. This structure causes a refractive index mismatch which makes the ZnS ARC layer less reflective. A similar examination was conducted for the bottom cell having a TCO layer (refractive index=2.447-1.953) on top of the Si substrate. For different values of the ZnS and TCO layer thickness, the fractions of photon current absorbed and reflected are summarised in Table I.

Table I. Influence of the ZnS and ITO Layers on the Percentage of Photons Absorbed and Reflected by the GaInP Cell and the Si Cell, Respectively

Cell	Thickness (µm)		Fractional Photon Current Absorbed (%)	Fractional Photon Current Reflected (%)	Efficiency (%)
GaInP	ZnS layer	10	68.7	28.6	13.7
		50	87.5	9.4	18.2
		100	70.8	25.8	14.3
		150	76.8	19.5	16.1
Si	ITO layer	10	72.9	0.5	13.3
		50	69.7	10.6	12.0
		100	62.3	15.9	11.1
		150	65.6	12.5	11.5

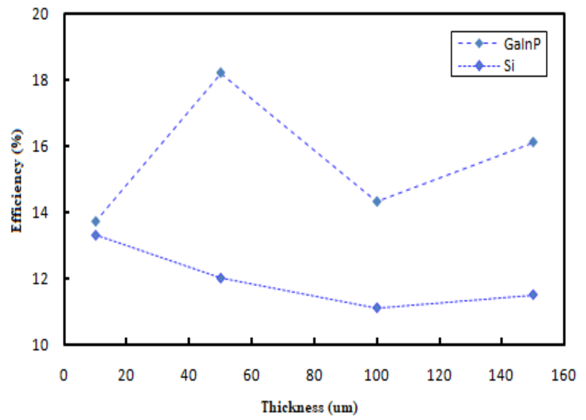

Fig .3. Dependence of efficiency on the thickness of ZnS ARC and ITO layer

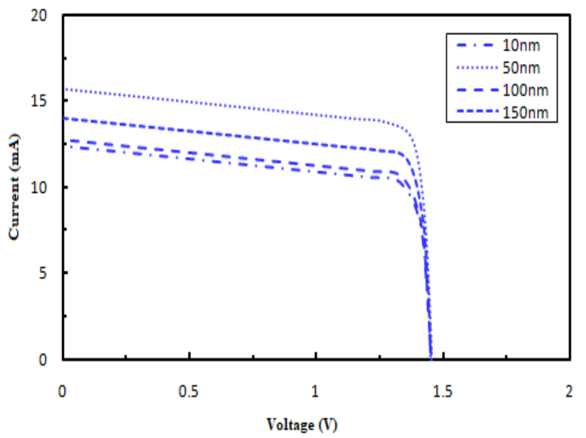

Fig .4. Current-Voltage characteristics of GaInP cell for different thickness of ZnS anti-reflective coating

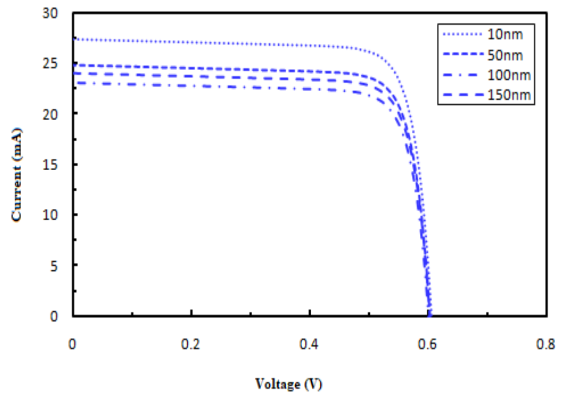

Fig .5. Current-Voltage characteristics of Si cell for different thickness of ITO layer

Fig. 3, 4 and 5 show that there is a strong dependence of the solar cell I-V characteristics on the thickness of the ZnS anti-reflection coating and the ITO layer. It can be observed from the I-V characteristics that for the GaInP cell the efficiency is maximum with a ZnS ARC coating thickness of 50nm. Also, the efficiency is maximum for an ITO layer thickness of 10nm for the Si cell. These results are in direct agreement with the data presented in Table I, which establishes that the percentage of photons absorbed by the base layer is greatest for the stated thicknesses.

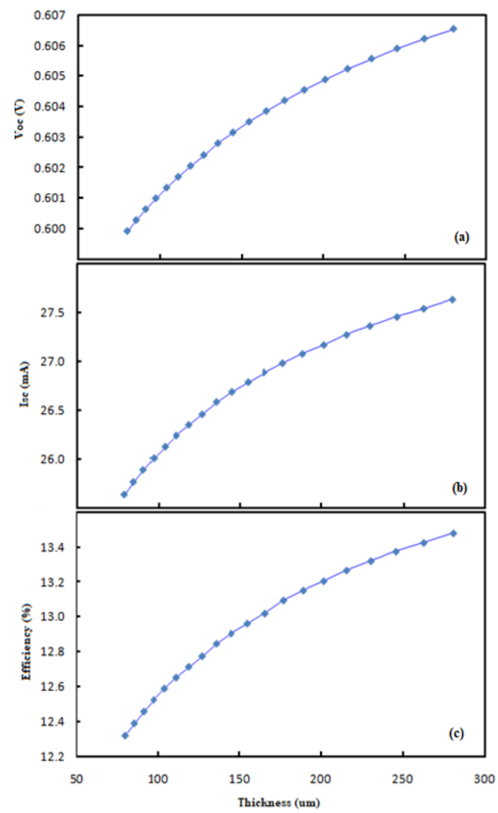

Fig .6. Influence of thickness of the Si bottom cell on (a) VOC (b) ISC (c) Efficiency

Fig. 6 shows the dependence of the open circuit voltage, short circuit current and the efficiency on the thickness of the Si cell. As the thickness of the cell increases, the interaction of the incident photons with the cell improves. Thus, for greater cell thickness the incident photons generate a bigger number of electron-hole pairs, which in turn increases the overall photocurrent in the cell improving the efficiency.

Table II. Optimised Parameters of the Top and the Bottom Cell Used for the Final Design

Parameters	**Si Cell**	**GaInP Cell**
Thickness (µm)	230	1.7
Dielectric Constant	11.9	11.8
Bandgap (eV)	1.12	1.86
Emitter Thickness (µm)	10	0.1
Emitter Doping Concentration ($/cm^3$)	$1x10^{17}$ (p-type)	$5x10^{17}$ (n-type)
Base Thickness (µm)	215	1.49
Base Doping Concentration ($/cm^3$)	$1x10^{16}$ (n-type)	$1x10^{16}$ (p-type)
BSF Thickness (µm)	5	0.1
BSF Doping Concentration ($/cm^3$)	$1x10^{17}$ (n-type)	$4x10^{18}$ (p-type)
Front Surface Recombination Velocity (cm/s)	10000	10000
Rear Surface Recombination Velocity (cm/s)	10000	10000

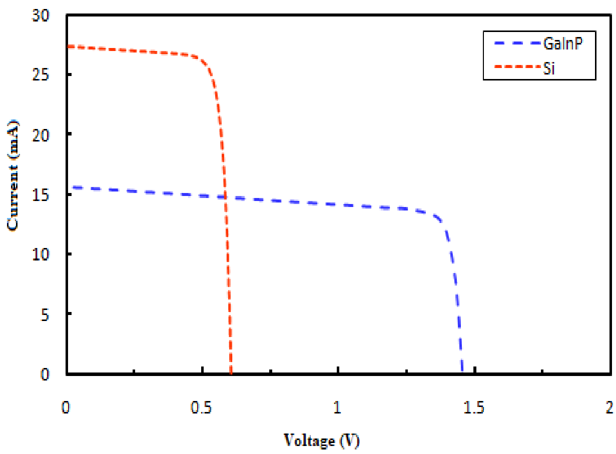

Fig .7. Current-Voltage characteristics of the optimised four-terminal photovoltaic cell

The theoretical model of the solar cell described in this investigation exceeds the experimental efficiency value of 25.6% [15] of a single junction Si solar cell. The efficiency of the tandem cell described in this paper is also close to the record one-sun efficiency of 31.1% [16] which was achieved with a monolithic GaInP/GaAs dual junction structure. The tandem cell theoretical efficiency of 31.5% for the structure under investigation in this paper is in close agreement with the practical efficiency of 29.8±0.6% obtained in S. Essig, M. A. Steiner, C. Allebé, J.F. Geisz, B. Paviet-Salomon, S. Ward, A. Descoeudres, V. LaSalvia, L. Barraud, N. Badel, A. Faes, J. Levrat, M. Despeisse, C. Ballif, P. Stradins, D.L. Young, "Realization of GaInP/Si dual-junction solar cells with 29.8% one-sun efficiency". An in-house efficiency of 31.5% was reported for a mechanically stacked interdigitated back contact dual junction solar cell. The Si bottom cell efficiency recorded therein was 12.5%, while the GaInP top cell demonstrated single junction efficiency of 19.1% [17]. Furthermore, it was shown that dual junction III-V/Si mechanically stacked and independently operated solar cell could reach cumulative one sun efficiencies of over 32% [18].

Table III: Summary of the Results

Cell	V_{OC} (V)	I_{SC} (mA)	Efficiency (%)
Si	0.6056	27.4	13.3
GaInP	1.455	15.7	18.2
Tandem	2.0606	15.7	31.5

IV. CONCLUSION

Studies performed on the mechanically stacked GaInP/Si based dual-junction solar cell structure achieved an accumulative one-sun efficiency of 31.5%. It can be observed that the overall efficiency of the solar cell is largely dependent on the efficiency of the top cell. The overall efficiency of the tandem cell is highly dependent on the thickness of the window layer, anti-reflection coating, ITO layer and the substrate thickness. Greater efficiencies can be achieved by increasing the open circuit voltage of the Si bottom cell and increasing the short circuit current of the GaInP top cell.

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