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Optimization of Single-Junction GaAs Solar Cell

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Abstract
GaAs solar cell has gained a lot of attention because of its band gap, 1.42 eV, which is close to the optimum for the standard solar spectrum. As a direct gap material it can absorb the light strongly above its band gap as well. This paper focuses at the effect of different parameters such as emitter/base thickness, emitter/base doping concentration, anti-reflection coatings (ARC) on the performance of GaAs solar cell. Synopsys TCAD has been used to simulate the GaAs solar cell. The simulation shows emitter with 900 nm thickness & 7×10^{17} cm^{-3} doping concentration and base with 2 µm thickness and 4×10^{18} cm^{-3} doping concentration are optimum to achieve the maximum performance from the GaAs solar cell. Simulation also shows, as ARC, Si_3N_4 will perform better than TiO_2 for the GaAs solar cell.

Keywords: solar cell, GaAs, TCAD, thickness, doping concentration, Si_3N_4, TiO_x.

I. INTRODUCTION

Silicon (Si) is not an ideal solar cell material as its band gap (1.1 eV) is smaller than the optimum (1.4 eV) for terrestrial solar energy conversion [1]. The absorption coefficient of Si is low, so a relatively thick layer of Si is required to absorb the sunlight effectively. The significant requirement for high purity silicon increase the cost, as well as the weight, of the cell. Another consideration is the temperature dependence of efficiency which makes Si less suitable for application under concentrated light and in space.

Gallium arsenide (GaAs) has a band gap of 1.42 eV at room temperature which is close to the optimum [2]. It is also a direct band gap material and strongly absorbs above the bang gap. Over visible wavelengths the absorption coefficient of GaAs is about ten times that of Si and only a few µm rather than hundreds of µm are needed for the active region of the solar cell. GaAs also has better temperature coefficient than Si. Solar cell efficiency tends to decrease with increasing temperature. In Si, increasing temperature also increases the number of phonons which eventually increases the recombination. GaAs solar cell also has higher electron saturation velocity and higher electron mobility compared to silicon solar cells [2]. Because of all these features, GaAs cells have raised interest, mainly for space application [3]. Surface recombination rate was a major problem that was preventing the development of GaAs solar cell initially and only 10% [4], [5] efficiency was achieved by GaAs solar cell at first. This problem was reduced by using a $Ga_{1-x}Al_x$ on the surface of GaAs [6]. $Ga_{1-x}Al_x$ has similar crystal parameters like GaAs which reduces the defects and recombination centers in the interface between these two semiconductors [7]. Thus the performance enhanced significantly and in the late 70s, an efficiency of 22% was reported [8]. Now a days this solar cell have reached an efficiency of around 20-25% [9].

This work focuses on different parameters and studies their effect on the performance of GaAs solar cell. All simulations were conducted using Synopsys TCAD.

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II. SIMULATION STRUCTURE

Figure 1 shows the structure of the GaAs solar cell simulated using Synopsys TCAD [10]. The structure is a stack of AlGaAs front surface field (FSF), n-type GaAs emitter, p-type GaAs base, AlGaAs back surface field (BSF), GaAs buffer layer and GaAs substrate. On top of the AlGaAs FSF layer, anti-reflective coating (ARC) and GaAs cap layers were created. Silver front and back contact were also placed at the very top and bottom of the cell structure.

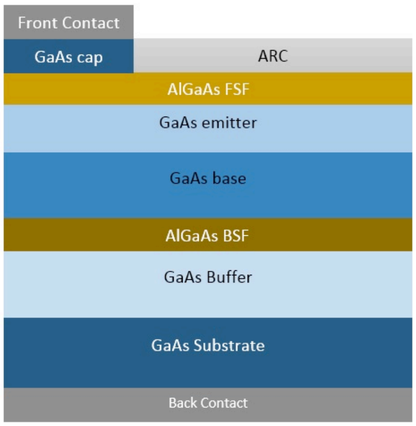

Fig. 1. Cross Section of simulated GaAs solar cell. (Figure not to scale)

III. Physics Based TCAD Model

In order to simulate the solar cells in Fig. 1, electrical and optical parameters of the materials were used from published literature. Transfer Matrix Method (TMM) from Synopsis Device was used and the solar cell was illuminated by a spectral illumination source of AM1.5G [11] and a monochromatic light source. The spectra were simulated by ramping the wavelength of the signal.

All electrical simulations were performed using the drift diffusion transport model. In this model, electrostatic Poisson equation and the carrier continuity equations for both electrons and holes were solved. Doping-dependent mobility model i.e. Shockley–Read–Hall (SRH) and Auger Recombination models were also included to consider bulk and interface recombination velocities. All optical simulations used the complex refractive index model and quantum yield model. Complex refractive index values of the materials had also been collected from the published data [12].

IV. Simulation Results and Discussion

The open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), fill factor (FF) are used to calculate the solar cell efficiency. The efficiency of the cell at the maximum power point can be calculated as follows:

$$\eta = \frac{P_m}{P_{in}} = \frac{I_{sc} V_{oc} FF}{P_{in}} \qquad (1)$$

Key parameters i.e. short circuit current density (J_{sc}), open circuit voltage (V_{oc}) and power conversion efficiency (η) of the solar cell were extracted to study the effect of different parameters on solar cell.

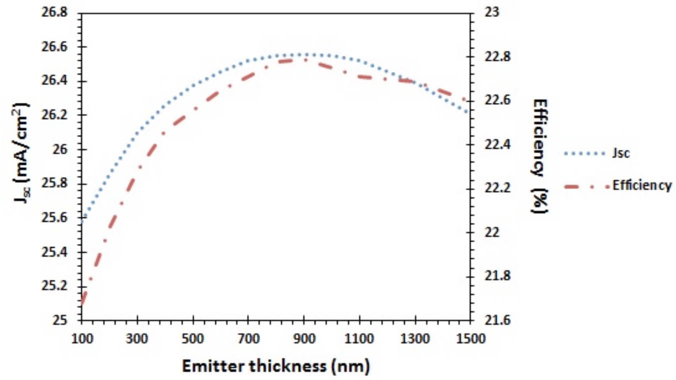

Fig. 2. Effect of emitter thickness on J_{sc} and efficiency of the GaAs solar cell.

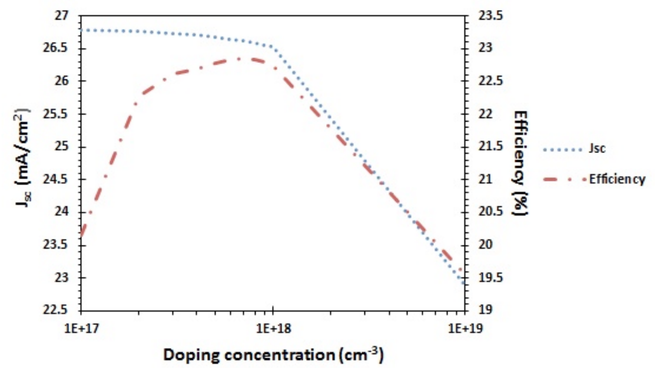

Fig. 3. Effect of emitter doping on J_{sc} and efficiency of the GaAs solar cell at 900 nm emitter thickness.

At first, GaAs emitter layer thickness was varied from 100 nm to 1500 nm. The maximum J_{sc} and efficiency were obtained for an emitter thickness of 900 nm. Any thicker or thinner emitter layer would result a loss in J_{sc} which results lower power conversion efficiency as can be seen in Fig. 2. The emitter doping concentration was also varied from $1\text{x}10^{17}$ cm^{-3} to $1\text{x}10^{19}$ cm^{-3} at 900 nm emitter thickness. The optimum doping concentration was found $7\text{x}10^{17}$ cm^{-3}. Any decrease or increase in doping results a performance drop of the GaAs solar cell. Figure 3 shows that after $1\text{x}10^{18}$ cm^{-3} the performance drops sharply which can be explained by the excessive recombination of the minority carrier. Table I & II summarize the J_{sc}, V_{oc}, FF and efficiency of GaAs cell for different emitter thicknesses and doping concentrations respectively.

TABLE I

Change in J_{sc}, V_{oc}, FF and Efficiency with Emitter Thickness.

	J_{sc} (mA/cm^2)	V_{oc} (v)	FF (%)	Efficiency (%)
100	25.58	1.004	84.36	21.68

	200	25.86	1.004	84.82	22.03
	300	26.10	1.005	84.98	22.28
	400	26.26	1.004	85.15	22.46
	500	26.38	1.004	85.14	22.56
Emitter Thickness (nm)	600	26.46	1.004	85.24	22.65
	700	26.52	1.004	85.26	22.71
	800	26.55	1.004	85.49	22.78
	900	26.56	1.004	85.49	22.79
	1000	26.55	1.003	85.59	22.75
	1100	26.52	1.003	85.36	22.71
	1300	26.39	1.003	85.73	22.69
	1500	26.21	1.003	85.95	22.60

TABLE II
CHANGE IN J_{SC}, V_{OC}, FF AND EFFICIENCY WITH EMITTER DOPING AT 900 NM EMITTER THICKNESS.

		J_{sc} (mA/cm^2)	**V_{oc} (v)**	**FF (%)**	**Efficiency (%)**
	1E+17	26.79	0.944	79.75	20.15
	2E+17	26.76	0.985	84.51	22.27
	3E+17	26.74	0.998	84.78	22.61
	4E+17	26.71	1.001	84.85	22.69
	5E+17	26.68	1.002	85.22	22.78
Doping concentration (cm^{-3})	6E+17	26.65	1.003	85.47	22.84
	7E+17	26.62	1.003	85.55	22.85
	8E+17	26.59	1.004	85.54	22.83
	9E+17	26.56	1.004	85.49	22.79
	1E+18	26.53	1.004	85.43	22.75
	1E+19	22.89	1.002	85.31	19.56

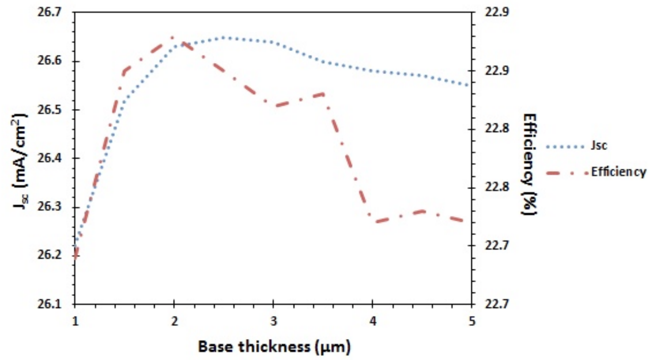

Fig. 4. Effect of base thickness on J_{sc} and efficiency of the GaAs solar cell at 900 nm emitter thickness and $7x10^{17}$ cm^{-3} emitter doping concentration.

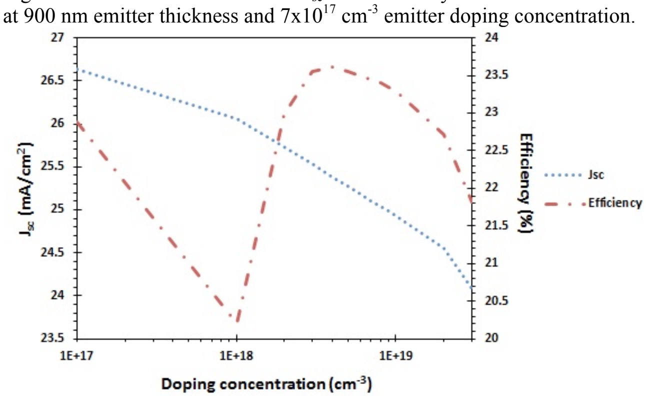

Fig. 5. Effect of base doping concentration on J_{sc} and efficiency of the GaAs solar cell at 900 nm emitter thickness & $7x10^{17}$ cm^{-3} emitter doping concentration and 2 µm base thickness.

After that, the thickness of the base layer had been varied from 1 µm to 5 µm for an emitter thickness and doping concentration of 900 nm and $7x10^{17}$ cm^{-3} respectively. It was found that at 2 µm base thickness, GaAs solar cell achieves the highest efficiency as can be seen in Fig. 4. Though the value of J_{sc} is higher at 2.5 µm than 2 µm, but because of the higher V_{oc} at 2 µm, the overall efficiency of GaAs solar cell is higher at 2 µm compared to 2.5 µm (see Table 3). The base doping concentration was also varied from $1x10^{17}$ cm^{-3} to $1x10^{19}$ cm^{-3} for an emitter thickness of 900 nm, emitter doping concentration of $7x10^{17}$ cm^{-3} and base thickness of 2 µm. The most optimized doping concentration was found to be $4x10^{18}$ cm^{-3} for which the highest efficiency, 23. 61%, was recorded which can be seen in Fig. 5. Table III & IV summarize the J_{sc}, V_{oc}, FF and efficiency of GaAs cell for different base thicknesses and doping concentrations respectively.

TABLE III
CHANGE IN J_{SC}, V_{OC}, FF AND EFFICIENCY WITH BASE THICKNESS AT 900 NM EMITTER THICKNESS AND 7X10^{17} CM^{-3} EMITTER DOPING CONCENTRATION.

		J_{sc} (mA/cm^2)	V_{oc} (v)	FF (%)	Efficiency (%)
Base Thickness (µm)	1.0	26.22	1.017	85.07	22.69
	1.5	26.52	1.010	85.27	22.85
	2.0	26.63	1.007	85.31	22.88
	2.5	26.65	1.005	85.34	22.85
	3.0	26.64	1.004	85.30	22.82
	3.5	26.60	1.004	85.50	22.83
	4.0	26.58	1.002	85.27	22.72
	4.5	26.57	1.002	85.37	22.73
	5.0	26.55	1.002	85.41	22.72

TABLE IV
CHANGE IN J_{SC}, V_{OC}, FF AND EFFICIENCY WITH BASE DOPING AT 900 NM EMITTER THICKNESS, 7X10^{17} CM^{-3} EMITTER DOPING CONCENTRATION AND 2 µM BASE THICKNESS

		J_{sc} (mA/cm^2)	V_{oc} (v)	FF (%)	Efficiency (%)
Base Doping (cm^{-3})	1E+17	26.63	1.007	85.31	22.88
	1E+18	26.06	0.963	80.54	20.21
	2E+18	25.73	1.036	86.22	22.99
	3E+18	25.53	1.051	87.77	23.56
	4E+18	25.38	1.055	88.19	23.61
	5E+18	25.27	1.056	88.26	23.56
	6E+18	25.18	1.057	88.27	23.50
	7E+18	25.10	1.058	88.30	23.45
	8E+18	25.04	1.058	88.31	23.40
	9E+18	24.98	1.059	88.29	23.35
	1E+19	24.93	1.059	88.26	23.30
	2E+19	24.55	1.058	87.47	22.72
	3E+19	24.08	1.057	85.73	21.82

In the next step two different types of ARCs, Si_3N_4 and TiO_2, were studied. The emitter thickness, emitter doping concentration, base thickness and base doping concentration were set to 900 nm, 7x10^{17} cm^{-3}, 2 µm and 4x10^{18} cm^{-3} respectively. Initially a random thickness of 55 nm was chosen for both the ARCs. Figure 6 shows the result of the optical simulation- transmission, reflection and absorption curves of the GaAs solar cell for both Si_3N_4 and TiO_2. This figure shows that the transmission through the GaAs solar cell remains almost same for both these ARCs. For Si_3N_4, GaAs solar cell shows lower reflection compared to GaAs solar cell with TiO_2. This means more light is absorbed by the GaAs solar cell that has Si_3N_4 as ARC which can be seen in Fig. 6 as well.

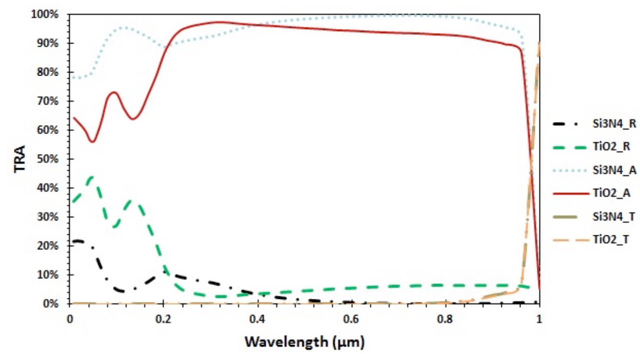

Fig. 6. Transmission, reflection and absorption curves of GaAs solar cell with TiO_2/Si_3N_4 as ARC at 900 nm emitter thickness, 7x10^{17} cm^{-3} emitter doping concentration, 2 µm base thickness and 4x10^{18} cm^{-3} base doping concentration.

Figure 7 shows the J_{sc} and efficiency of the GaAs solar cell with TiO_2/ Si_3N_4 as ARC. The result shows the same trend as predicted by the optical simulation. GaAs solar cell with Si_3N_4 as ARC has higher J_{sc} and efficiency compared to GaAs solar cell with TiO_2 as ARC. Figure 8 shows the J-V curves of both the GaAs cells with TiO_2 and Si_3N_4. After that, effect of Si_3N_4 thickness on GaAs cells has been studied which is shown in Fig. 9. Maximum J_{sc} and efficiency were found when Si_3N_4 has a thickness of 55 nm. The J_{sc} and efficiency were found to be low below 55 nm because of higher sheet resistance. As Si_3N_4 also absorbs some light, any increase of thickness after 55 nm results significant light absorption by Si_3N_4 layer which lowers the overall performance of the cell. Table 5 summarizes the change in J_{sc}, V_{oc}, FF and efficiency of GaAs cell for different Si_3N_4 thicknesses.

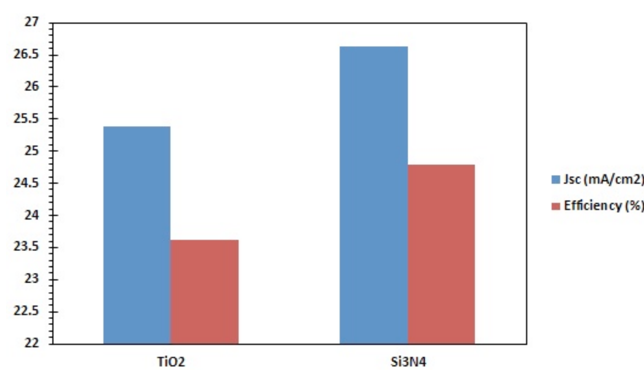

Fig. 7. Comparison of J_{sc} and Efficiency of GaAs solar cell with TiO_2/Si_3N_4 as ARC at 900 nm emitter thickness, 7x10^{17} cm^{-3} emitter doping concentration, 2 µm base thickness and 4x10^{18} cm^{-3} base doping concentration.

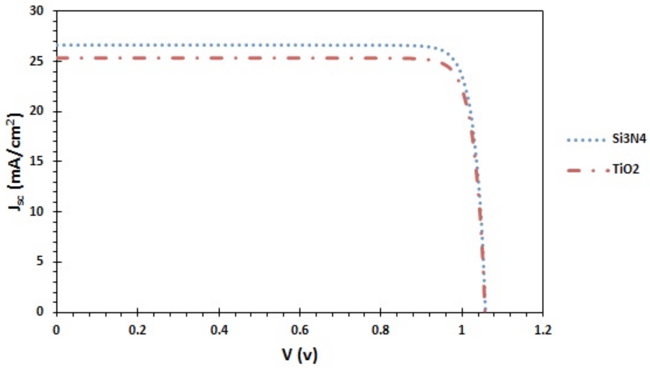

Fig. 8. J-V curves of GaAs cells with TiO_2 and Si_3N_4 as ARC at emitter thickness, emitter doping concentration, base thickness and base doping concentration of 900 nm, 7x10^{17} cm^{-3}, 2 µm and 4x10^{18} cm^{-3} respectively.

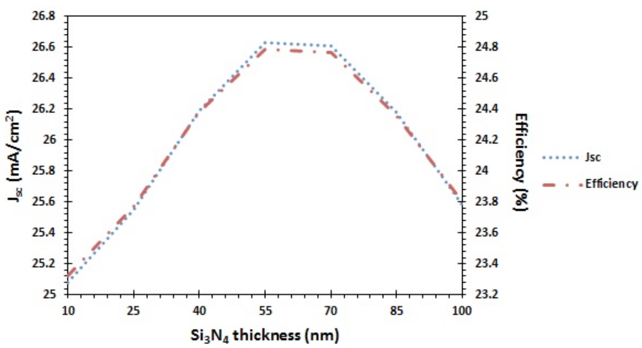

Fig. 9. Effect of Si_3N_4 thickness on J_{sc} and efficiency of the GaAs solar cell at 900 nm emitter thickness, 7x10^{17} cm^{-3} emitter doping concentration, 2 µm base thickness and 4x10^{18} cm^{-3} base doping concentration.

TABLE IV

CHANGE IN J_{SC}, V_{OC}, FF AND EFFICIENCY WITH Si_3N_4 THICKNESS AT 900 NM EMITTER THICKNESS, 7X10^{17} CM^{-3} EMITTER DOPING CONCENTRATION, 2 µM BASE THICKNESS AND 4X10^{18} CM^{-3} BASE DOPING CONCENTRATION

		J_{sc} (mA/cm^2)	V_{oc} (v)	FF (%)	Efficiency (%)
Si_3N_4 Thickness (nm)	10	25.08	1.054	88.19	23.32
	25	25.55	1.055	88.19	23.77
	40	26.19	1.055	88.18	24.38
	55	26.63	1.056	88.18	24.79
	70	26.61	1.056	88.18	24.77
	85	26.18	1.055	88.18	24.36
	100	25.58	1.055	88.19	23.8

V. CONCLUSION

In summary, different parameters of a GaAs solar cells were studied to optimize its performance. It was found that GaAs solar cell with 900 nm emitter thickness, 7x10^{17} cm^{-3} emitter doping concentration, 2 µm base thickness and 4x10^{18} cm^{-3} base doping concentration would perform with highest efficiency. TiO_2 and Si_3N_4 were also investigated as ARC and it was found that Si_3N_4 outperforms TiO_2 and the most optimized thickness for Si_3N_4 was found to be 55 nm.

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