OPTIMIZATION OF MULTIJUNCTION SOLAR CELL BY WAFER RAY TRACER FOR DEVELOPMENT OF HIGH PHOTOGENERATED CURRENT

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Abstract

Optical losses limit the excess carriers generation in absorber part of multijuction (MJ) solar cell. The generation of excess carriers is directly proportional to photogenerated current solar cell. Therefore, reduction of optical losses is fundamentally important for improving the power conversion efficiency. Thickness of layers strongly influences the performance of MJ solar cell. In this study we simulated a MJ solar cell of Air/ZnO/SiC/c-Si/a-Si(n)/Al structure using Wafer Ray Tracer (WRT) simulation software and optimized the thicknesses of the layers for photogenerated current. The simulation result shows that without SiC layer, only 57.48% of incident light is absorbed and generates 26.85 mA/cm2 photogenerated current in solar cell. A 70 nm thickness of optimized SiC layer is increasing the light absorption 22.16% and photogenerated current 38.54%. Result shows that there is no transmission of light through the absorber layer. The MJ solar cell without Back Surface Field (BSF) layer of a-Si(n) shows photogenerated current of 37.05 mA/cm2 which can be improved to 37.24 mA/cm2 with a 100 nm thickness of a-Si(n). The c-Si absorber layer shows highest absorptance within 500 nm-1000 nm wavelength of light spectrum with 100 nm thickness of a-Si(n). An a-Si(n) BSF layer at the back surface minimizes the effective back-surface recombination velocity and improves the collection probability of minority carriers of solar cell. Furthermore a 100 nm Al rear contact improves the photogenerated current of MJ solar cell to 37.25 mA/cm2. An Al rear contact layer improves the mechanical strength of c-Si absorber layer. The electrical property of Al improves the excess carriers' collection probability of MJ solar cell.

Keywords: *Wafer Ray Tracer, Simulation, Multijunction Solar Cell, Photogeneration, Back Surface Field.*

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1. INTRODUCTION

The Sun is a powerful source of energy that can be used to heat, cool, and light our homes and businesses. The amount of solar energy that falls on the earth's surface in 40 minutes equals to the total annual energy consumption of the entire world's people. Put differently, 27 years' worth of worldwide energy consumption equals only one day's worth of solar energy hitting the earth. All the energy in the earth's reserves of coal, oil, and natural gas is equal to just 20 days of energy produced by the sun, but only 1% of that solar energy is used to generate power [19].

A variety of technologies can be used to convert sunlight to usable energy. Solar cell is one of the most recent technologies which is used to covert light energy to electricity directly. The emitted light from the sun fall on solar plate and light particle photons are absorbed by solar material which generates a photocurrent at the output of solar cell. The amount of photocurrent generation at output of solar cell depends on the photon absorption capability of materials used in solar cell. Silicon which is the most dominated material in current existing technologies for designing of solar cell. An important part of a solar cell is the absorber layer, in which the photons of the incident light are efficiently absorbed resulting in a creation of excess electron-hole pairs. Therefore photocurrent density is increased by increasing of electron-hole pair generation within cell [1].

The cost of Si solar cell has been decreasing gradually due its material and manufacturing cost. The efficiency of commercially available single junction crystal silicon (c-Si) solar cells is almost equal to its theoretical efficiency [2]. But due to some remarkable reasons like band gap limitation, optical losses in cell, photon absorption capability of materials, short of new materials available for solar cell, charge separation techniques etc. a single junction silicon solar cell cannot achieve conversion efficiency higher than 30% [4]. One of the main reasons behind the limitation of efficiency is optical losses in solar cell. Photogenerated current density totally depends on generation of excess carriers in the cell after absorption of photon from the sunlight [1][3].

Since optical losses limit the efficiency of photovoltaic cell, it is very difficult to achieve efficiency higher than 30% with a single junction solar cell under 1-sun illumination. However, a tandem structure can be designed to achieve a higher efficiency solar cell [5].Over the last five years, the efficiency of triple-junction solar cell has increased from 41.1% [6] to 42.3% [7]. The highest reported efficiency of triple junction solar cell so far has 43.5±2.5% [8].One suitable way to further improve the efficiency of a tandem solar cell is to increase the number of junction [5][9]. M. Nell and A. Barnett have designed a spectral p-n junction model for tandem solar cell [9].

Optical losses in solar cell can be reduced with a deposition of anti reflection coating (ARC). An ARC model minimizes the reflection of light from its surface which ensures the high photocurrent in solar cell. However, light management is an important part for improving the performance of thin-film solar cells. Solar cell demands an advanced analysis on light scattering and trapping inside the cell structures [10].Another important part in solar cell is designing of collector in the front side and the back side of solar cell surface. A proper design of collector can increase the collection probability which increase the flow of charges through the external circuit [11].

Crystalline silicon(c-Si) cells are also dominating the current solar market. Single junction c-Si solar cells are rapidly approaching theoretical efficiency. Now solar cell industries are capable of manufacturing large area cell with efficiency greater than 24% [2][13]. Present research on solar cell are able to achieve efficiency more than 30% [14][15]. Recent research on solar cell is growing interest in multi junction solar cells that combine high-absorption coefficient amorphous silicon (a-Si) with current high-efficiency crystalline silicon (c-Si). This study on multi junction solar cells are able to achieve efficiencies above 30% [12][15][16][17].However a more study is needed in designing and simulating of multijunction solar cells.

In this paper, authors have studied on a multijunction solar cell (MJ) of amorphous silicon (a-Si) and crystalline silicon(c-Si) with different front and rear thin-film layers. The purpose of this study is to increase the total photogenerated current in MJ solar cell. We optimized the total photogenerated current and thickness of different layers of the MJ solar cell.

2. MJ SOLAR CELL STRUCTURE

The device structure of the proposed MJ solar cell is utilizing Air/ZnO/SiC/c-Si/a-Si(n)/Al. Surrounding of the front surface of this MJ solar cell was considered as air. The Zinc Oxide (ZnO) layer is used as front contact layer whereas the rear contact layer was optimized with Aluminum (Al). A layer of Silicon Carbide (SiC) was used between ZnO and c-Si layers. Front contact ZnO layer is also used as front surface reflector. A stack of ZnO/SiC can be used as an improved reflector. The absorber and Back Surface Field (BSF) layers are a c-Si and a-Si(n) respectively. Optical losses can be calculated from reflection by front surfaces, escaping from the structure and transmission through the absorber layer. The device structure of this MJ solar cell has shown in Fig.1.

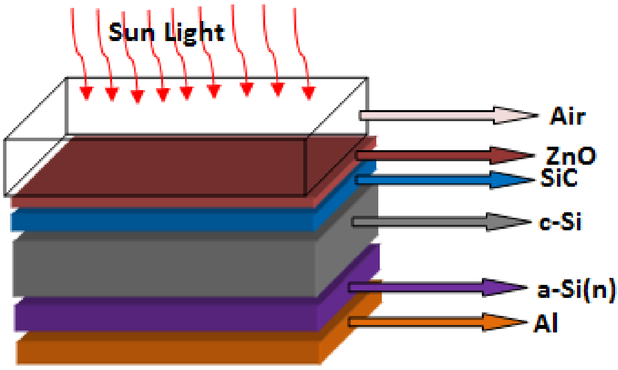

Fig -1: Device Structure of MJ Solar Cell.

3. SIMULATION METHODOLOGY

In this study we have simulated a MJ solar cell using Wafer ray tracer (WRT) simulation software.WRT is a powerful tool to simulate and test a solar cell structure under a chosen illumination spectrum of light. It can be used to improve optical properties of solar cell structure. WRT permits to asses all optical losses and light trapping in different layers of solar cell structure. Therefore total photogenerated current density and total optical losses can be determined from total reflection, transmission and absorption of light in different layers of solar cell.WRT simulator combines Monte Carlo ray tracing with thin film optics. It calculates the photogenerated current density in wafer through numbers of light rays is created above the front surface of defined structure for solar cell. The gain (photogeneration) and the all losses (reflection, transmission and absorption) in different layers of solar cell are recorded for each ray. The final gain and losses are determined by averaging a large number of rays [18].

In this simulation, some constant parameters have been used for simplification purpose. We have considered zenith incident angle of direct light on the front surface at 0˚. The zenith angle is the light incidence angle for a horizontal surface, i.e. the angle between the sun's direct rays and a line perpendicular to the horizontal surface at a given point. It is computed on an hourly basis. Spectrum of sunlight kept in AM1.5g standard condition. The surface morphology for both front and rear are kept in planner. The following constant parameters of incident light are used for simulation of MJ solar cell is shown in Table -1

Table -1: Constant parameters of incident light

Parameters	Value
Minimum Wavelength	300 nm
Maximum Wavelength	1200 nm
Wavelength interval	20 nm
Number of rays per run	5000
Maximum total rays	50000
Maximum bounces per ray	1000
Intensity limit	0.01%

In this paper, authors studied the reflectance, absorptance, transmittance and photogenerated current with variation of different layer thickness and final optimized structure of MJ solar cell obtained based on the best performance of the structure. The study also shows the properties and optical behavior of different materials used in MJ solar cell within incident light spectrum.

4. SIMULATION RESULTS AND DISCUSSION

Optimization of MJ solar cell was obtained based on the thickness variation of different layers for development of photogenerated current.

4.1 Thickness Variation of Front Film Layers

In order to enhance the coupling of the light, the designing of front contact as well as front coating layer is crucial part in high efficiency thin film silicon solar cells. Transparent conducting oxides (TCOs) based on ZnO are promising for application in thin film solar cell and various optoelectronic devices. Therefore the upper front contact layer of ZnO should fulfill two important requirements: one is high transparency in solar spectrum and another is high electrical conductivity. The structure Air/ZnO(5nm)/c-Si(200µm)/a-Si(n)(100nm)/Al(100nm) without SiC is showing that total photogenerated current(Jph) in the cell is only about 26.85 mA/cm2 .Only 57.48 % of incident light participates in photogeneration of the cell (Lph). About 34.71% of incident light reflected from external surface (LLRext) and shows external reflection current loss (JRext) is about 16.22 mA/cm2. Others losses of solar cell are shown as follows: reflected escape current loss (JResc)= 2.921 mA/cm2 corresponding to reflected escape light (LLResc)= 6.254%, absorbed rear film current loss (JArear)= 0.71 mA/cm2 corresponding to light absorption in rear film (LLArear)= 1.521%, front film absorption current loss (JAfront)=0.006 mA/cm2 corresponding to light absorption in front film (LLAfront)= 0.014%.

The simulation results are showing that maximum optical loss occur in external surface of the cell. Therefore designing of front surface is a challenging part to minimize optical losses in solar cell. Numbers of material are available for designing of solar cell in semiconductor industries. But SiC is one of the dominated material for its distinct properties such as a wide bandgap semiconductor, high radiation resistance, stability at high temperatures, and high thermal conductivity [20].Another advantage of SiC is that both the elements of carbon and silicon are very abundant and non-toxic. A deposition of SiC passivation layer on c-Si can improve the optical properties of solar cell. Deposition can be carried out with different methane to silane (CH4/SiH4) ratios and different values for radio frequency power by plasma enhanced chemical vapor deposition (PECVD). The band gap of SiC varies 1.03-2.08 eV and intrinsic coefficient varies 104-105 cm-1 [21].

After deposition of SiC capping with ZnO, the simulation result shows that the total photogenerated current (Jph) is increasing dramatically. The structure Air/ZnO(5nm)/SiC(70nm)/c-Si(280µm)/a-Si(n)(100nm)/Al(100nm) of solar cell shows following results: Jph= 37.20 mA/cm2, Lph= 79.64% ; JRext = 4.668 mA/cm2, LLRext = 9.99% ; JResc= 3.727 mA/cm2, LLResc= 7.987% ; JArear = 0.78 mA/cm2 , LLArear= 1.684%, (JAfront)=0.32 mA/cm2, (LLAfront)= 0.688%. The total, external and escape reflectance of this optimized structure are shown in the Fig.2.

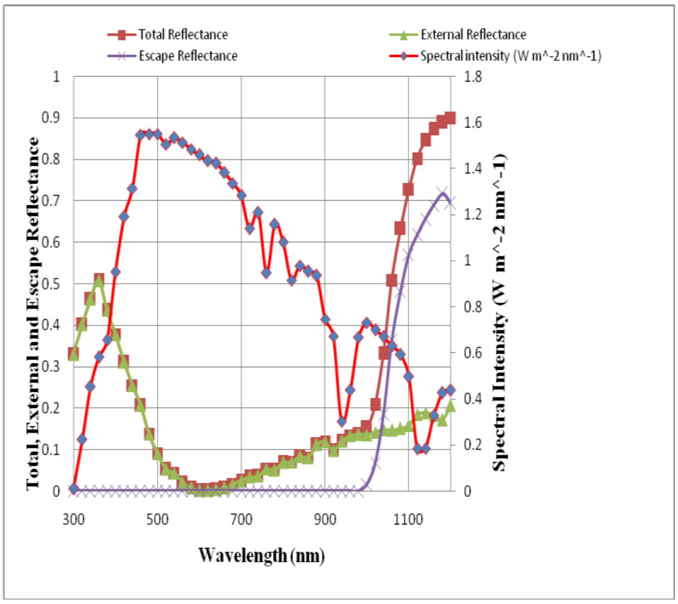

Fig -2: Reflectance of cell in 70 nm thickness of SiC.

The simulation result shows that total reflection decreases about 22.16% and external reflection decreases about 24.72% with deposition a 70 nm thickness of SiC layer whereas escape reflection increases only about 1.7%. But if the overall improvement of cell is considered, the increasing of escape reflection with deposition of SiC can be neglected.

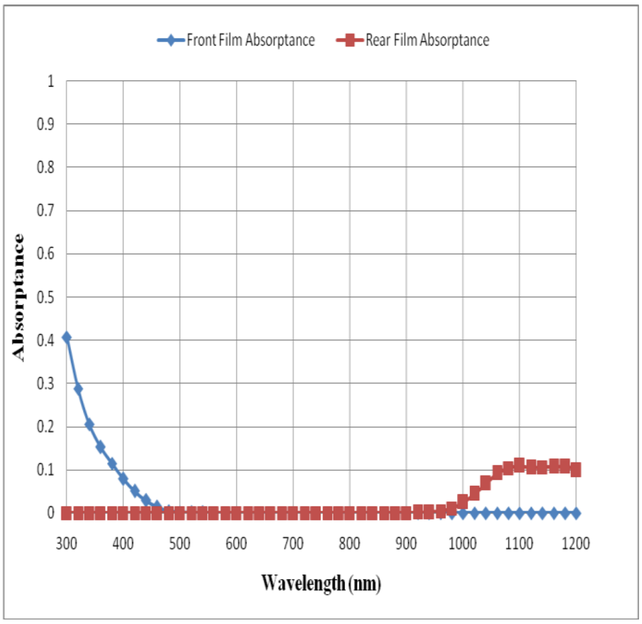

Fig -3: Front film and Rear Film Absorptance in 70 nm thickness of SiC

There is no absorption of light in front anf rear film layer within 500 nm-1000nm. Absorptance front film is slightly increasing about 0.4 below 500 nm wavelength of light whereas rear film absorptance is slightly increasing about 0.1 after 1000 nm wavelength of light. The front film and rear film absorptance with deposition a 70 nm thickness of SiC have shown on Fig.3.

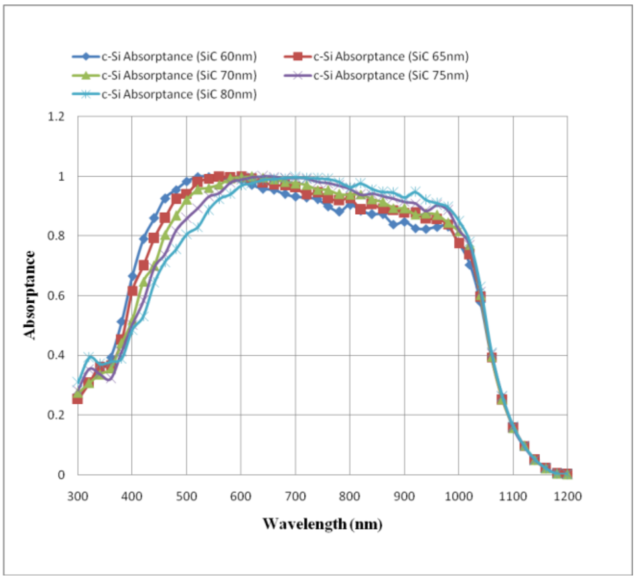

Fig -4: c-Si absorptance in different thickness of SiC

The Cryatalline silicon (c-Si) is the absorper layer of this MJ solar cell. Almost all of the incident light absorbed in this layer. There is no transmission of light through the c-Si absorber layer. Absorptance of c-Si layer with different thickness of SiC layer is showing in Fig.4. The highest photogenerated current obtained at 70 nm thickness of SiC layer whereas the photogenerated current decreases above and below of 70 nm thickness SiC layer. The total photogenerated current of this solar cell structure in different thickness of SiC layer are graphically shown in Fig.5. Therefore simulation result shows that after deposition of ZnO/SiC capping layers on front surface of the solar cell, the total photogenerated current is increasing about 38.54%.

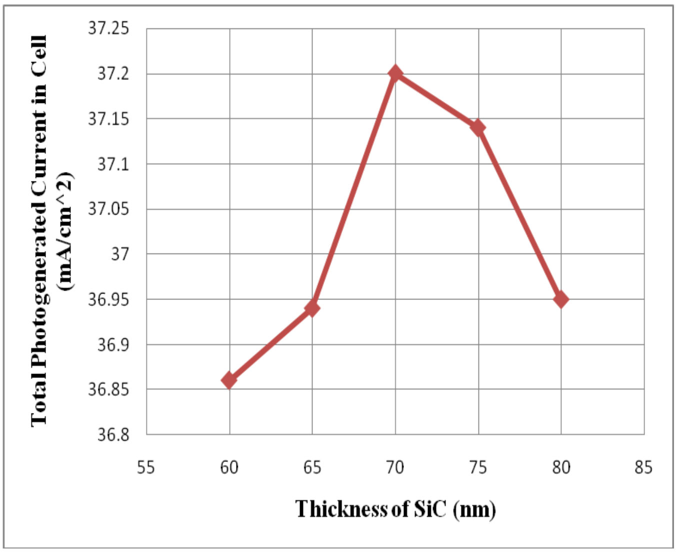

Fig -5: Total photogenerated current in different thickness of SiC

4.2 Thickness Variation of Back Surface field (BSF)

The a-Si(n) layer between c-Si and rear contact can be used as a Back Surface Field (BSF). The photogeneration in absorber layer can be increased using this BSF layer. A BSF layer can be deposited in back surface of solar cell using screen printed technology which is also an effective method to improve the efficiency of solar cell [22]. The simulation result shows that photogenerated current increases when a BSF layer deposited on rear side of the solar cell. The simulation results with deposition of BSF layer are shown as follows: without BSF Jph = 37.05 mA/cm2 and Lph= 79.15% ; with BSF of 100 nm thickness Jph=37.24 mA/cm2 and Lph= 79.64%. Therefore an optimized BSF structure has been obtained at 100 nm thickness of a-Si(n) layer. The rear surface reflectance with deposition of BSF layer has shown in Fig.6.

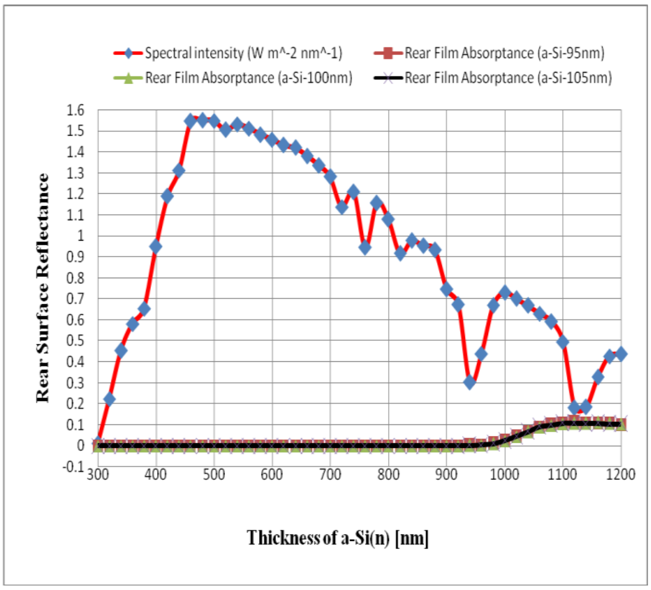

Fig -6: Rear surface reflectance with deposition of BSF layer.

The c-Si absorber layer shows highest absorptance within 500 nm-1000 nm wavelength of light spectrum. Absorption of light in c-Si layer increases from 300 nm whereas absorption decreases after 1000 nm wavelength of light. Absorptance of c-Si layer with different thickness of a-Si(n) BSF has shown in Fig.7. The highest photogenerated current 37.24 mA/cm2 has been obtained at 100 nm and 105 nm thickness of a-Si(n) BSF layer. Therefore 100 nm or 105 nm thickness of a-Si(n) layer can be considered as an optimized BSF layer of this MJ solar cell because of highest absorption in c-Si absorber layer and high value of photogenerated current in the cell at these thickness. The total photogenerated current in different thickness of a-Si(n) BSF layer has shown in Fig.8.

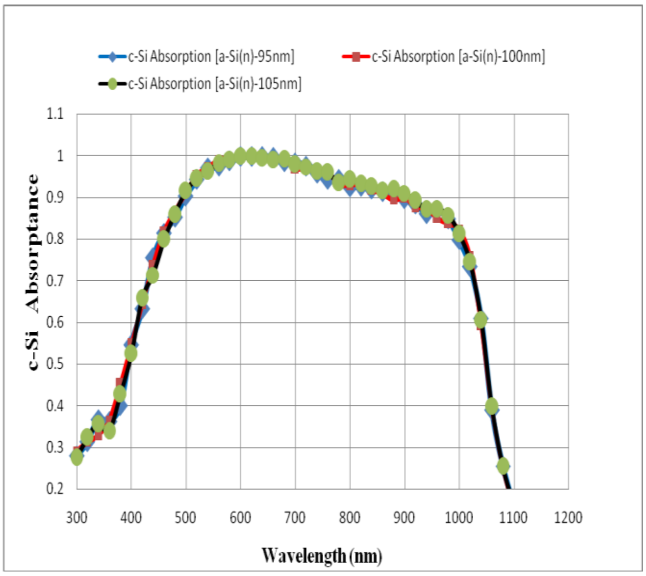

Fig -7: c-Si Absorptance in different thickness of a-Si(n) BSF layer.

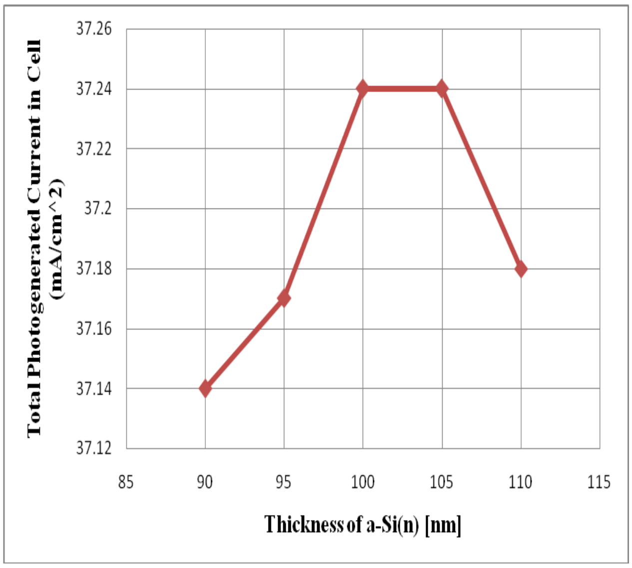

Fig -8: Total photogenerated current in different thickness of a-Si(n) BSF layer.

An a-Si(n) BSF layer at the rear surface minimizes the effective back-surface recombination velocity and improves the collection probability of minority carriers of solar cell. The interface between c-Si and rear contact behave like a p-n junction and an electric field forms at the interface which introduces a barrier to minority carrier flow to the rear surface. Thus a higher level of minority carrier concentration is maintained in bulk of the solar cell [22].

4.3 Thickness variation of Al Rear Contact

A back contact is used to collect the excess photogenerated carriers in solar cell. In this study we have optimized back contact layer in different the thickness of Aluminum (Al) material. The simulation of MJ solar cell shows that the highest absorption of c-Si layer obtained between 500 nm and 1000 nm wavelength of light with different thickness of Al back contact. The highest photogenerated current of 37.25 mA/cm2 obtained at 100 nm of Al back contact. The absorptance of c-Si absorber layer and the total photogenerated current of MJ solar cell with different thickness of Al have shown in Fig.9 and Fig.10 respectively.

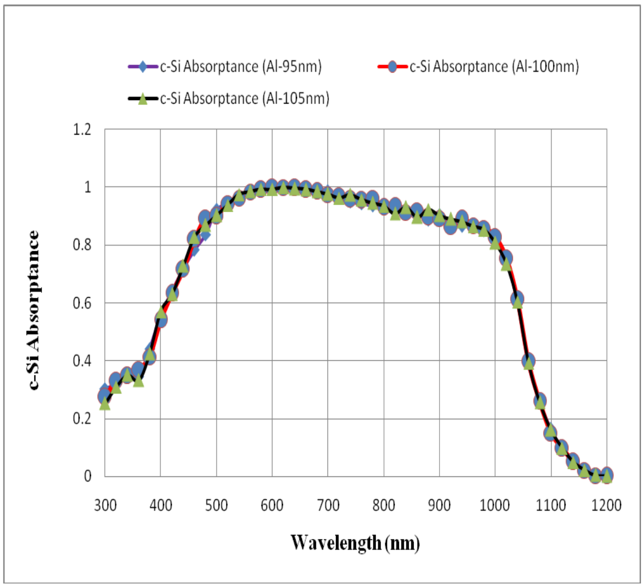

Fig -9: c-Si absorptance in different thickness of Al back contact.

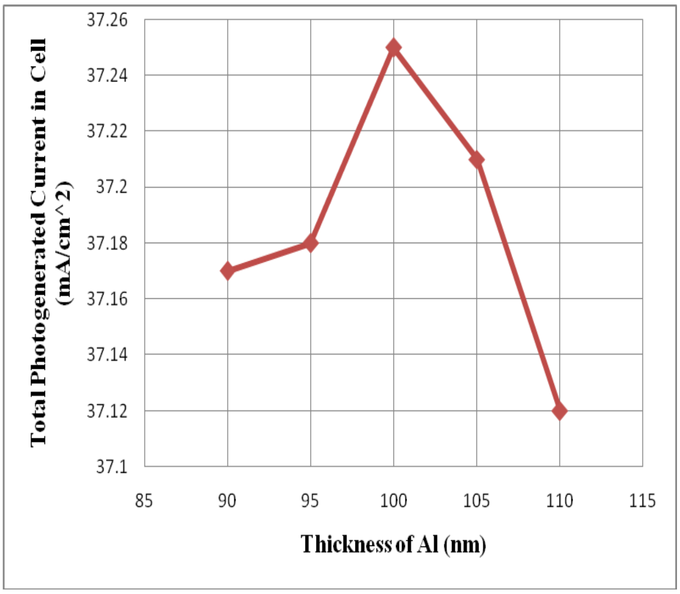

Fig -10: Total photogenerated current in different thickness of Al back contact.

Al material has been chosen as the back contact of MJ solar cell for its some unique advantages over others high conductivity materials. Firstly, Al shows higher plasticity property to silicon wafer which improves the performance of MJ solar cell. Since the Young's modulus of the Al is about 44.5 GPa, the layer of Al can induce some plasticity at the outer surface of the silicon wafer. This plasticity at the outer surface of silicon wafer can serve as a barrier for possible crack at silicon wafer surface. This behavior of Al improves the mechanical strength of silicon wafer in MJ solar cell [23]. Secondly, the electrical conductivity and thermal conductivity of Al are 3.8×107 S/m and 235 W/ (m K) respectively. The electrical property of Al improves the excess carriers' collection probability of MJ solar cell.

5. CONCLUSION

In this study all of the layers were simulated in different thickness within incident light spectrum. The MJ solar cell without SiC layer shows a very low level excess carrier generation in absorber layer. Only 54.48% of incident light are absorbed within in the solar cell results 26.85 mA/cm2 photogenerated current at output. A 70 nm thickness of optimized SiC layer is increasing the photogenerated current about 38.54%. With deposition of a SiC layer reduces the optical losses in MJ solar cell and increasing the path length of incident light within the solar structure which increases the amount of light absorption in c-Si absorber layer. Therefore SiC is an excellent material which can be used as an antireflection coating for a solar cell. Further increasing of photogenerated current was obtained with deposition a-Si(n) BSF layer between c-Si and Al back contact. A BSF layer not only increase the photogenerated current in solar cell but also provide a good passivation layer for c-Si absorber layer [24]. Therefore, c-Si absorbed is another interesting aspect in which a light trapping scheme can be combined to achieve better performance characteristics. Furthermore Al back contact improves the performance of MJ solar cell. An optimized Al back contact shows a 37.25 mA/cm2 current at output. An Al back contact layer improves the mechanical strength of silicon wafer in MJ solar cell. Another important advantage of Al material is that it is a low cost material compare to others material. Therefore, this study provides a direction in research to improve the performance of MJ solar cell.

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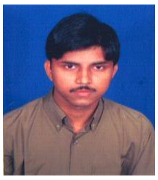

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