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Performance Analysis on Conversion Efficiency of Heterojunction with Intrinsic Thin layer (HIT) Solar Cell by PC1D Simulation

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Abstract : This paper presents the detailed performance analysis on conversion efficiency of Heterojunction with Intrinsic Thin layer Solar Cell by PC1D Simulation. The silicon "Heterojunction with Intrinsic Thin layer (HIT)" solar cell is one of the promising options for a cost effective, high efficiency photovoltaic system. The influences of emitter, intrinsic layer and Back Surface Field (BSF) on the photovoltaic characteristics of solar cell are discussed. The performance of the solar cell is determined by using one-dimensional solar cell simulation software PC1D. The efficiency is observed under ONE-SUN, AM1.5G solar radiation, and constant intensity of 0.1 W/cm^2. The simulation results show that the key role of the intrinsic layer inserted between the amorphous silicon and crystalline silicon substrate is to increase the quantum efficiency. BSF can increase conversion efficiency more than 2 percentage compared with HIT solar cell with no BSF. The thickness of BSF has little effect in efficiency. Higher doping concentration leads to higher conversion efficiency. This BSF requires the doping concentration exceeding $1X10^{20}cm^{-3}$. By optimizing the parameters, the overall efficiency achieved by simulation is around 21.05%.
Keywords: Heterojunction, HIT, solar cell, amorphous/crystalline silicon, PC1D, simulation.

Introduction

In "HIT" cells, the PN junction and the Back Surface Field (BSF) layer formation steps take place at a relatively low temperature (~200°C) using hydrogenated amorphous silicon (a-Si:H) deposition technology, whereas in normal crystalline silicon (c-Si) cells the wafer has to be raised to ~800°C for junction and BSF layer formation by diffusion[1.] This means not only a lower thermal budget, but also cost reduction from thinner wafers. Thin intrinsic layers on either face of the c-Si substrate effectively passivate c-Si surface defects, and thereby achieve a significant improvement in the junction characteristics. The reason for the insertion of the intrinsic layer relates to the problem of achieving both adequate hole and electron mobility in doped a-Si: H material. The goal is to ensure that virtually all the photon absorption occurs in the intrinsic layer. Subsequent improvements in conversion efficiency is possible through the realization of a back surface field with the HIT structure[2].

The major advantage of the HIT cell structure is its perfect surface passivation which allows for very high open-circuit voltages (V_{OC}) over 710 mV. The higher V_{OC} results in not only higher conversion efficiency but also an improved temperature coefficient, which is another practical advantage for outdoor use[3]. In contrast the achieved currents are only moderate. This is due to the parasitic absorption of photons in the amorphous emitter on the front side. The diffusion length is quite small so that internal quantum efficiency for short wavelength photons is relatively low. Therefore, a cell structure with front hetero-emitter is always a compromise between high voltage, good transport properties and blue response.

This paper presents the simulation results for the electrical and optical behavior of HIT solar cells. Numerical modeling is widely used to gain better understanding into the details of the physical operation of solar cells. Several modeling tools such as PC1D, AMPS[4,5], SCAPS[6], and ASA[7] have been developed over the years for numerical modeling of PV devices. Numerical simulation is routinely performed in developing and studying crystalline silicon solar cells. Amongst the various programs in use, PC1D is more or less a standard in the field. PC1D was originally developed by Basore and coworkers at Sandia National Labs and was further developed at UNSW, Australia.

The Structure of Hit Cell

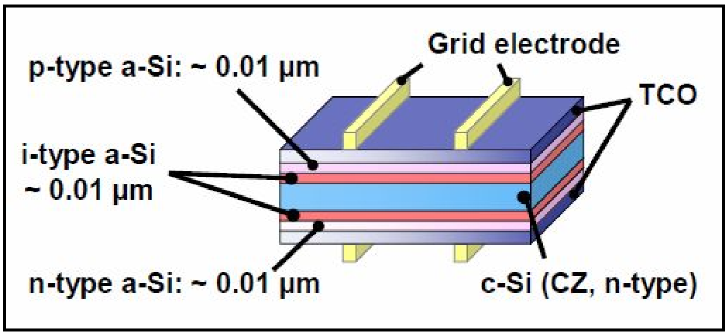

Figure-1. Structure of HIT Cell [1]

The HIT solar cell is an original SANYO structure in which an intrinsic (i-type) amorphous silicon (a-Si) layer and a p-type a-Si layer are deposited on a randomly textured n-type crystalline silicon (c-Si) wafer, so that a pn heterojunction is formed. On the opposite side of the c-Si wafer, i-type and n-type a-Si layers are deposited to obtain a Back Surface Field (BSF) structure. On both sides of the doped a-Si layers, Transparent Conductive Oxide (TCO) layers and metal grid electrodes are formed. All of the processes described above are done at low temperature (<200˚C), so that any thermal damage to the components of the cell can be avoided. By inserting the high-quality intrinsic a-Si layer between the c-Si wafer and the doped a-Si layer using a low-damage process, the surface dangling bonds of c-Si can be well passivated. This effective passivation allows us to obtain a HIT solar cell with a high V_{OC} compared to a general c-Si based solar cell fabricated by the thermal diffusion of ~900˚C. Its high V_{OC} leads to not only high conversion efficiency but also an excellent temperature coefficient. This good temperature coefficient of HIT solar cells can bring higher benefits to consumers because the annual amount of output power that the HIT solar cells produce is more than that of a conventional type. In addition, as shown in Fig.1, the HIT solar cell has a symmetrical structure that provides two features. One is the applicability of the cell to a so-called bifacial module which can generate more electricity than an ordinary module, and the other is a stress-free structure, which is very important for thinner wafer processing.

While SANYO develops HIT solar cells with a very thin intrinsic a-Si: H (i) layer inserted between different type a-Si: H and c-Si, it should be noted that there is a controversy on the need of such a layer. Some authors claim that it is beneficial, while others get good results without it and do not see significant improvements if they introduce it [8]. It is of significance that the absorption of sunlight in a-Si:H is very different from the absorption in crystalline silicon. The effective bandgap of a-Si-H is higher than that of crystalline Si, the absorption coefficient in a-Si:H becomes higher by over one order of magnitude compared to crystalline silicon, which means that a thin film of a-Si:H in the thickness range of 1 µm is enough to absorb considerable sunlight.

Modeling of the Hit Cell

C1D computer program is a widely used numerical modeling program for simulation of crystalline semiconductor solar cells. It uses a finite-element numerical method for solving the coupled nonlinear equations for carrier generation, recombination and transport in the device. It can be used for simulation of device performance, as well as a tool for new users to understand the fundamentals of solar cell physics[9]. The merits of using PC1D are high calculation speeds, broad list of material and physical parameters and an instinctive user interface. PC1D can be used to calculate the current-voltage characteristics and spectral quantum efficiency of the solar cell. It also has a large number of options for analysis both in time domain and spatial domain. The PC1D computer program is limited to one-dimensional modeling. Batch mode of PC1D allows to rapidly performing optimization study for a particular parameter rather than varying the parameters frequently. In batch mode, for each input parameter, the range to be varied over, the number of different values and type of variations (logarithmically or linearly) are to be specified.

Assumptions for simulation

i. Fixed conditions of illumination 'ONE-SUN' with the standard AM1.5G and the ambient temperature of 300 K are considered.
ii. Material parameters such as electron and hole diffusivity, front-surface and real-surface recombination, and diffusion length have been assumed in this study [2,10].
iii. The recombination losses in the ITO/emitter-layer and c-Si/Al interface of device have not been considered.
iv. The defect stares in each layer and interface including emitter-layer, emitter-layer/i-layer interface, i-layer and i-layer/c-Si interface have not been taken into account in the present simulation modeling.

Modeling Parameters

For the simulation using PC1D, typical device parameters (like device area, surface texture, optical coating) and layer parameters (like bandgap, electron affinity, doping concentration, mobility) are listed in Table-1 and Table-2, respectively. The operation temperature is set at 300 K; the AM1.5 source is adopted as the solar radiation with a power density of 100 mW/cm^2, and the effective wave range is 300-1100 nm. Figure-2 describes the device structure and layer thickness modeled in PC1D simulator.

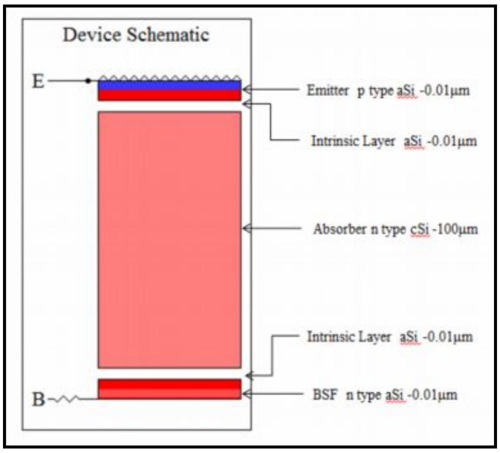

Figure-2: Device structure and layer thickness in PC1D model

Table-1: Typical device parameters used as input for computer simulation

Device Area	100 cm^2
Front Surface	Textured
Exterior Front Reflectance	3%
Exterior Rear Reflectance	95%
Emitter Contact	Enabled
Base Contact	0.0015 Ω
Internal conductor	0.3S
Light Source	One-SUN (AM1.5G, 100 mW/cm^2)

Table-2: Typical layer parameters used as input for computer simulation

Parameter	a-Si(p)	a-Si(i)	c-Si(n)	a-Si(n)
Thickness (μm)	0.01	0.01	100	0.01
Dielectric constant	11.9	11.9	11.9	11.9
Electron affinity (eV)	3.9	4	4.05	4
Bandgap (eV)	1.72	1.72	1.12	1.72
Electron mobility ($cm^2V^{-1}s^{-1}$)	5	5	1041	10
Hole mobility ($cm^2V^{-1}s^{-1}$)	1	1	412	3
Doping Concentration (cm^{-3})	$1x10^{20}$	0	$1.5x10^{17}$	$1x10^{19}$
Bulk Recombination (μs)	1000	-	1000	1000
Front-Surface Recombination (cm/s)	10^7	10^7	10^7	10^7
Rear-Surface Recombination (cm/s)	10^6	10^6	10^6	10^6

Simulation Results

With the solar cell simulator PC1D, we have determined the performance-limiting factors of the HIT solar cell by investigating its current-voltage characteristics and spectrum quantum efficiency. In this section we present different examples of simulation that are possible with PC1D on a personal computer.

The influence of the intrinsic layer thickness

HIT solar cell structure has a-Si:H(i) layer between the p+ doped amorphous silicon and c-Si(n+) from the front, and n+ doped a-Si cathode and c-Si(n+) on the back side of solar cell, as shown in Figure-1 and 2. This layer increases the quantum efficiency of the structure, especially in smaller wave lengths, without significant impact on the value of voltage V_{OC}.

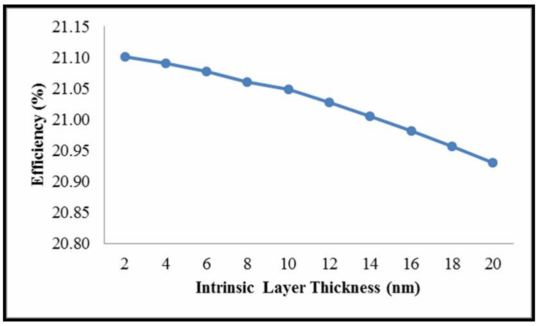

Figure-3: Efficiency variations as a function of intrinsic layer thickness

As can be seen from Figure-3, the conversion efficiency of HIT is up to 21.12% when thin intrinsic layer is inserted. But, as intrinsic layer thickness increases, the conversion efficiency decreases. When the thickness of intrinsic layer reaches 12 nm, the conversion efficiency of HIT solar cell with intrinsic layer is equivalent to solar cell with no intrinsic layer. Compromising the production processes and conversion efficiency, the optimal intrinsic layer thickness should be set at 10nm.

The effect of the BSF thickness

The Back Surface Field (BSF) refers to a region at the back surface of the solar cell which will act as a barrier for the minority carriers, thereby effectively reducing the recombination of the light-generated charge carriers. The BSF is used to enhance to the I_{SC} and V_{OC} to some extent. BSF can be formed by using a layer doped with the same type, but of higher doping concentration.

Table-3 lists the effect of the BSF thickness on the Efficiency, V_{OC} & I_{SC} characteristics of HIT solar cell. We can observe that when the thickness increases, V_{OC} and I_{SC} are nearly unchanged, and only a slight change in cell efficiency (η). So, the efficiency can be considered as independent with the thickness. If the required thickness is very thin, production time can be dramatically saved. The optimal BSF thickness should be set to 10 nm or even less because if the required thickness is very thin, production time can be greatly saved.

Table-3: Effect of BSF Thickness

BSF Thickness (nm)	V_{OC} (V)	I_{SC} (A/cm^2)	Efficiency η
2	0.727	3.501	21.04
6	0.727	3.501	21.04
10	0.727	3.5	21.02
14	0.727	3.5	21.02
20	0.727	3.5	21.02

The effect of the BSF doping concentration

Figure-4 shows the influence of BSF doping concentration on the photovoltaic characteristics of solar cell.

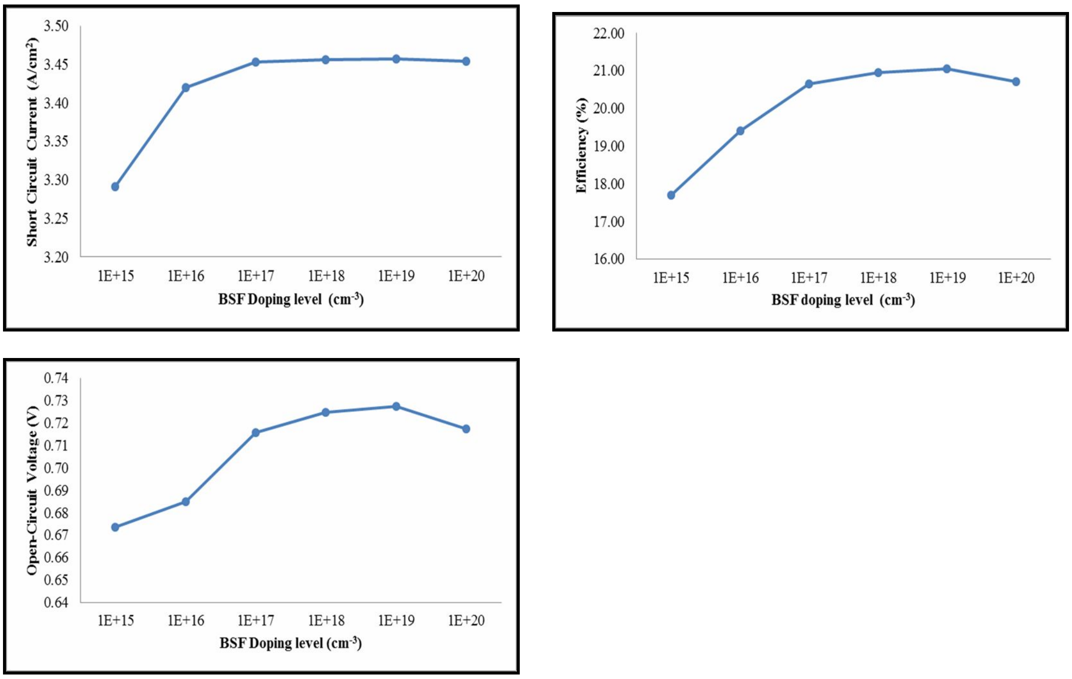

Figure-4: The influence of the doping concentration of BSF

From figure-4, we can see that the doping concentration must reach a certain value, preferably more than $1X10^{19}cm^{-3}$, before the conversion efficiency increased by 0.5%. With increasing doping concentration, the open-circuit voltage and short-circuit current are increased. This can be attributed to the BSF band structure. When the doping concentration is low, the reflection role of BSF is not clear, and the barrier on the carrier transport can be reduced by increasing the doping concentration, which explains the high doping concentration is guarantee of good BSF.

The influence of the wafer thickness

Figure-5 shows the variation in efficiency as a function of wafer thickness. As the thickness increases the efficiency increases.

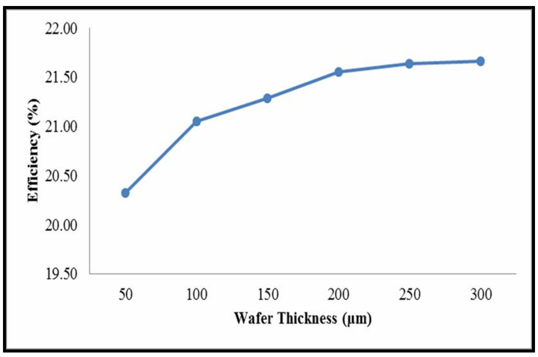

Figure-5: Wafer thickness variations Vs Efficiency

The decrease in the wafer thickness is very effective for reducing the fabrication cost of the solar cell. However, thinner Si wafers generally cause some problems. The first problem is a weakness in mechanical strength. A thin Si wafer is not only easily cracked, but is also easily warped by mechanical and thermal stresses. The warping of the cell might cause a drop in the process yield for the solar module assembly process. The second is a decrease in photocurrent. Because the absorption coefficient of Si in the near-infrared region is low, incident photons in the near-infrared wavelength penetrate the wafer without being absorbed into the Si. This causes a decrease in I_{SC}. And, the third is a drop in V_{OC}. When the recombination rate of minority carriers on the Si surface is much higher than that in bulk Si, the ratio of the carrier recombination on the Si surface increases as the thickness of the Si wafer decreases. In this case, the V_{OC} of the thinner cell decreases[11].

Optimization of Surface Recombination Velocity

Recombination of electrons and holes also occurs at the solar cell surfaces. The speed at which electron-hole pairs recombine at the surface is called the Surface Recombination Velocity, SRV. The performance variation with respect to front surface recombination velocity, S_f is carried out. The back surface recombination velocity, S_b is kept constant at 1000 cm/s, while S_f is varied at 100 to $1X10^6$ cm/s. For convenience, this variation is carried out at a high minority carrier lifetime Si wafer, say, 1000 µs. Figure-6 shows the plot of the simulated efficiency versus S_f.

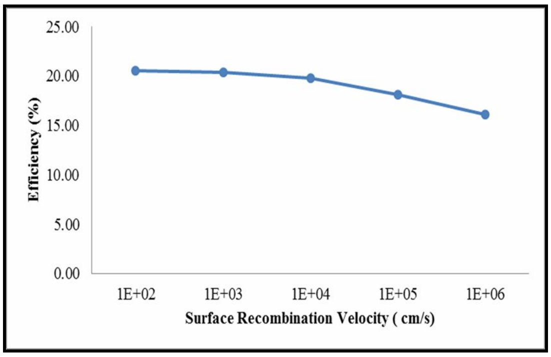

Figure-6: Surface Recombination Velocity Vs Efficiency

As expected, the conversion efficiency reduces for increasing surface recombination velocity. For optimum efficiency, the value of SRV is kept as 1000 cm/s.

Observations on Quantum Efficiency

Figure-7 shows the IQE and EQE curve of the HIT Solar Cell. The EQE increase in the short wavelength range (400–900 nm) probably resulted from the reduced absorption losses in the TCO and a-Si:H layers using the SiN and passivation layers with better transparency.

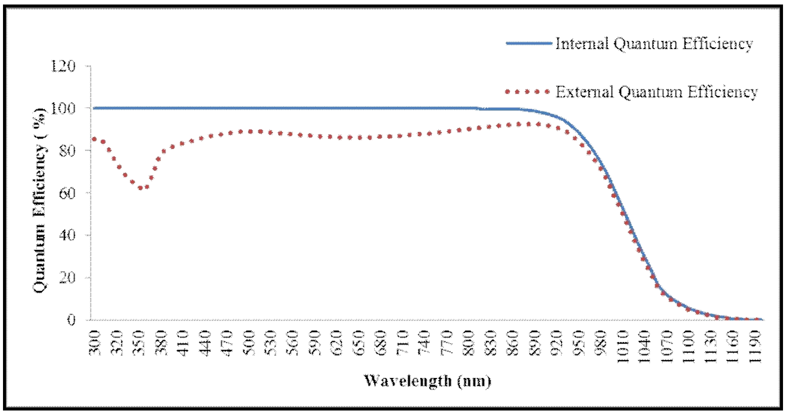

Figure-7: Quantum Efficiency Curve

Conclusions

HIT solar cell is simulated with PC1D software. The simulation results suggest that the increase of the intrinsic layer thickness, efficiency is decreased, and the optimum thickness is chosen to be 10 nm. This layer effectively increases the quantum efficiency of the structure, especially in smaller wave lengths, without significant impact on the value of voltage Voc.

The cell efficiency is independent of the BSF thickness, while reasonable doping can improve efficiency more than 2 percentage. Though the cell efficiency increases with increasing wafer thickness, the optimum thickness of the wafer is chosen to be 100 µm, because thinner wafers effectively reduce the fabrication cost of the solar cell. However, thinner wafers may cause problems like wafer cracking due to thermal and mechanical stresses, and drop in V_{OC} and I_{SC}. So, care should be taken while choosing the optimum thickness of the wafer. After optimizing the all the simulated parameters of the solar cell, the best solar cell with V_{OC}=0.72 V, I_{SC}=3.457 mA/cm^2, and η=21.05% has been achieved.

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