Research Article

Amorphous Silicon Single-Junction Thin-Film Solar Cell Exceeding 10% Efficiency by Design Optimization

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The conversion efficiency of a solar cell can substantially be increased by improved material properties and associated designs. At first, this study has adopted AMPS-1D (analysis of microelectronic and photonic structures) simulation technique to design and optimize the cell parameters prior to fabrication, where the optimum design parameters can be validated. Solar cells of single junction based on hydrogenated amorphous silicon (a-Si:H) have been analyzed by using AMPS-1D simulator. The investigation has been made based on important model parameters such as thickness, doping concentrations, bandgap, and operating temperature and so forth. The efficiency of single junction a-Si:H can be achieved as high as over 19% after parametric optimization in the simulation, which might seem unrealistic with presently available technologies. Therefore, the numerically designed and optimized a-SiC:H/a-SiC:H-buffer/a-Si:H/a-Si:H solar cells have been fabricated by using PECVD (plasma-enhanced chemical vapor deposition), where the best initial conversion efficiency of 10.02% has been achieved ($V_{oc} = 0.88$ V, $J_{sc} = 15.57$ mA/cm² and FF = 0.73) for a small area cell (0.086 cm²). The quantum efficiency (QE) characteristic shows the cell's better spectral response in the wavelength range of 400 nm–650 nm, which proves it to be a potential candidate as the middle cell in a-Si-based multijunction structures.

1. Introduction

The performance of solar photovoltaic cells depends on its design, material properties, and fabrication technology. Photovoltaic (PV) researchers present improved cells over the period of time, although the overall process is quite complex, expensive, and time consuming. Numerical simulation is the best approach for solar cell researchers, which help to find out an optimized structure with good fitted parameters. As a result fabrication complexity, costs, and time reduce significantly. The major objectives of numerical modeling and simulation in solar cell research are testing the validity of proposed physical structures, geometry on cell performance, and fitting of modeling output to experimental

results. The numerical modeling has become indispensable tools for designing a high-efficiency solar cell. Numerical modeling is increasingly used to obtain insight into the details of the physical operation of thin-film solar cells. Over the years, several modeling tools specific to thin-film PV devices have been developed. A number of these tools have been reached in a mature status and are available to the PV community. A driving force for the development is the complicated structure of thin-film PV devices. The internal optical and electronic operation of these cells is not possible if there is a lack of precise modeling. Numerical modeling is necessary for the realistic description of thin-film PV devices. On the other hand, analytic models have been used to improve understanding of the operation of the cells and to

provide a proper guidance for their design since the earliest time of modern solar cells. The analytical descriptions are possible only under certain assumptions and simplifications.

Hydrogenated amorphous silicon (hereafter, a-Si:H) thin film is a good optoelectronic material candidate for solar cell applications as it has high optical absorption coefficient ($>10^5 \text{ cm}^{-1}$), adjustable bandgap, and low temperature deposition capability. The optical bandgap up to 1.7 eV lies near the energy at which high solar energy conversion efficiencies are expected. The bandgap of a-Si:H can be tuned from 1.6 to 1.8 eV. The conversion efficiency of hydrogenated amorphous silicon (a-Si:H) single-junction thin-film solar cells has gradually been improved from 2.4% [1] to 10.1% [2]. The hydrogenated amorphous silicon (a-Si:H) solar cell progress has been started from the invention of first Schottky device with an efficiency of 2.4% by Carlson and Wronski [1] and Kabir et al. [3]. However, the first great breakthrough came with the growth of amorphous silicon from silane (SiH_4) plasma by Chittick et al. [4]. And the second major breakthrough was the substitutional doping by phosphine (PH_3) or diborane (B_2H_6) to the plasma during growth of n-type and p-type materials [5]. These outstanding properties of a-Si:H as an amorphous semiconductor generated enormous interest and started a large research effort worldwide [6]. Materials quality, device structure, and deposition technique are very important for improving solar cell efficiency [3]. There are several fabrication methods such as PECVD (RF, VHF, and Microwave), hot-wire CVD, photo CVD, sputtering, ECR CVD, and PBD downstream have been applied for improving cell performance [3, 7]. Among these methods, PECVD is the most successful method for the fabrication of a-Si:H solar cells that has been used for the fabrication of single-junction a-Si:H solar cells.

The efficiency of solar cell is the resultant outcome of its open circuit voltage (V_{oc}), short circuit current (J_{sc}), and fill factor (FF). For improving the efficiency of a solar cell, it is necessary to upgrade the above-mentioned parameters. In order to improve the device performance of a-Si:H solar cells, emphasis should be given mainly on higher short circuit current (J_{sc}) by developing light trapping scheme [8] and another one is to improve V_{oc} by applying new device design techniques with different a-Si alloys. A new device structure has been introduced by using hydrogenated microcrystalline silicon ($\mu\text{c-Si:H}$) as an active layer for solar cells in 1994 by the IMT group at the University of Neuchâtel in Switzerland [9]. They achieved an initial efficiency of 4.6% for a $\mu\text{c-Si:H}$ p-i-n single-junction solar cell with almost no light-induced degradation. Meanwhile, they developed the so-called "micromorph" a-Si/ $\mu\text{c-Si}$ tandem solar cell concept and achieved 12% stabilized efficiency [10]. The advance light trapping system-intermediate reflector in micromorph solar cell reduced light-induced degradation of about 1.64% [11]. Saito et al. (2005) presented a-Si:H/ $\mu\text{c-Si:H}$ / $\mu\text{c-Si:H}$ triple-junction solar cells with initial efficiency of 13.1% and light-induced degradation about 7.2% [12]. Many other attempts were taken by several research groups for improving V_{oc} , such as applying wide bandgap window layers (a-SiC:H, $\mu\text{c-SiO:H}$, nc-Si:H, etc.) in a-Si solar cells and inserting buffer

layers at p/i and i/n interfaces [13, 14]. The structure of a-SiC:H/a-SiC:H-buffer/a-Si:H/a-Si:H single-junction amorphous silicon thin-film solar cell model has been designed and optimized and finally fabricated according to the best design achieved in numerical simulation to validate it.

2. Design and Optimization

Thin-film hydrogenated amorphous silicon (a-Si:H) single-junction solar cell model has been designed and analyzed for exploring optimized structure for higher stabilized efficiency by using analysis of microelectronic and photonic structures (AMPS-1D) device simulator [15] which is shown in Figure 1. The conversion efficiency of a solar cell can be increased significantly with the improvement of materials properties and subsequently the designs and structures of the cell. An intrinsic absorber layer (a-Si:H) is enclosed between a p-type (a-SiC:H) and an n-type doped layer (a-Si:H). The p-layer functions as window layer through which the light enters. Photons that are absorbed in the i-layer create an electron-hole pair. The electric field induced across the i-layer by the p- and n-layers causes the electrons to drift towards the n-layer and the holes towards the p-layer. At the doped layers, the charge carriers are collected by electrical contacts and contribute to the output power of the solar cell. In the device modeling, wide bandgap a-SiC:H is used as p-doped window layer to reduce absorption losses. Moreover, V_{oc} also increases for its wider bandgap. It is well known that V_{oc} is sensitive to p-layer and p/i interface. As optical absorption at the p-layer limits J_{sc} , wider optical gap material is always desired for improving J_{sc} [16]. The p-type graded a-SiC:H buffer layer was used to mitigate the p/i interface effect which has a great influence on V_{oc} [17]. The design parameters have been adopted from some standard references (AMPS-1D) to investigate the variation of efficiency, V_{oc} , J_{sc} , and FF with the variation of thickness, bandgap, doping concentrations of p- and n-layers, and the dependence of efficiency on operating temperature. The values of different material parameters fed into AMPS-1D are shown in Tables 1 and 2.

The front TCO ($\text{SnO}_2\text{:F}$) has been applied for reducing reflection loss. The effect of ZnO:B along with metal contact (Ag/Al) was used to reduce the transmission loss through the back contact. The front and back TCO layers should have low electrical resistive and high optical transmittance in the visible wavelength range. Silver is inserted as back contact for its low resistivity ($2 \times 10^{-6} \Omega\text{-cm}$) to reduce the reflection losses through all layers. To increase the J_{sc} , the low resistive ($2.6 \times 10^{-2} \Omega\text{-cm}$) and high optical transparent ZnO:B layer is applied between n-layer and Ag as transparent back contact. However, ZnO/Ag has the capability to overcome the adhesion problem between a-Si and metal contact [18].

2.1. Performance Analysis of a-Si:H Solar Cell. In a-Si-based solar cells, i-layer thickness optimization is one of the fundamental factors which influence the reduction of material costs and improve collection efficiency. The multijunction solar cells utilize solar spectrum effectively with thinner

FIGURE 1: Schematic view of a-Si:H single-junction solar cell.

TABLE 1: The input parameters used in modeling the single-junction a-Si: H solar cell.

Material/parameters	SnO ₂ :F	p-layer a-SiC:H	p- (buffer) layer a-SiC:H	i-layer a-Si:H	n-layer a-Si:H	ZnO:B
W (nm)	50–150	10–20	2–9	100–1300	15–30	50–200
ϵ_r	9	11.9	11.9	11.9	11.9	9
μ_n (cm ² /Vs)	60	20.0	20.0	20.0	20.0	33
μ_p (cm ² /Vs)	6	2.0	2.0	2.0	2.0	8
N_a (cm ⁻³)	1.3×10^{19}	3.0×10^{18}	6.0×10^{18}	—	—	—
N_d (cm ⁻³)	—	—	—	—	8.0×10^{19}	8.0×10^{18}
E_g (eV)	3.7	1.9	1.9	1.65–1.95	1.75	3.3
N_c (cm ⁻³)	2.2×10^{18}	2.5×10^{20}	2.5×10^{20}	2.5×10^{20}	2.5×10^{20}	2.2×10^{18}
N_v (cm ⁻³)	1.8×10^{19}	2.5×10^{20}	2.5×10^{20}	2.5×10^{20}	2.5×10^{20}	1.8×10^{19}
χ (eV)	4.8	4.0	3.8	4.0	3.8	4.5

TABLE 2: General layer parameters.

Parameters	Front contact	Back contact
Barrier height (ϕ_{bo}/ϕ_{bL})	PHIBO = 1.45 eV	PHIBL = 0.08 eV
Electron recombination velocity	SNO = 1×10^7 cm/s	SLN = 1×10^7 cm/s
Hole recombination velocity	SPO = 1×10^7 cm/s	SPL = 1×10^7 cm/s
Reflection coefficient	RF = 0.02	RB = 0.8

absorber layers in different component cells and minimize recombination generation losses. Thus, the multijunction solar cell has a good impact on improving output voltage [19]. Electrons and holes generated in doped layers usually do not contribute to the photocurrent for their short life time. In p-i-n single-junction solar cell, p-layer should be as

thin as possible to allow maximum light into the following layers. To find the optimum structure, the i-layer thickness has been varied from 100 to 1300 nm, and the highest efficiency of 19.62% has been obtained at a i-layer thickness of 500 nm which is shown in Figure 2. A similar result has been observed in previous work [20]. In this work, the optimized intrinsic layer thickness (500 nm) reduced significantly compared with other finding— 700 nm [19], 600 nm [21], and 840 nm [22], respectively. FF and V_{oc} gradually decreased with the increase of i-layer thickness. The substantial fall in V_{oc} with the increase of i-layer thickness can possibly correlate to the associated increase of defect densities. Higher defect densities affect the electric field and carrier collection, eventually yielding in poor V_{oc} [23]. This decrease in V_{oc} might be averted with the introduction of a wide bandgap buffer layer, which reduces shunt resistance and prevents leakage current through the p/i

FIGURE 2: Photovoltaic characteristics for various absorber layer (a-Si:H) thickness.

interface and i/n interface [24]. J_{sc} monotonically increased up to 800 nm, and then it saturates.

2.2. Optimization of a-Si:H Absorber Layer Bandgap. The energy of incident light gradually decreases with the increase of absorber thickness. The high energetic photon will be absorbed in top absorber layer. Therefore, bandgap can be gradually decreased for successive absorber layers in multijunction configuration. To optimize the bandgap of a-Si:H single-junction solar cells for middle cell of triple junction configuration, bandgap has been varied from 1.65 to 1.95 eV. Figure 3 represents the variation of efficiency with the change of bandgap of a-Si:H layer. The optimum bandgap has been observed at 1.75 eV which corresponds to the maximum efficiency of 19.62%. The intrinsic absorber layer optimum bandgap of 1.7 eV [25] and 1.75 eV [26] has been used in top cell of micromorph a-Si:H/ μ c-Si:H solar cell configuration and in a single-junction a-Si solar cell, respectively.

2.3. Effect of Operating Temperature on Cell Performance. Solar cell performance generally decreases with increasing

FIGURE 3: Effect of i-layer bandgap on cell performance.

FIGURE 4: Operating temperature gradient.

temperature, mainly due to increased internal carrier recombination rates, caused by increased carrier concentrations. The other performance parameters such as open-circuit voltage (V_{oc}), short-circuit current (J_{sc}), and fill factor (FF) are also temperature dependent. V_{oc} and FF decrease with temperature and J_{sc} increases slightly with T . The rate of decrease of V_{oc} with temperature is controlled by the bandgap energy (E_g), shunt resistance (R_{sh}), and its rate of change with T . Finally temperature effects on solar cell decrease the efficiency. This general temperature dependence of solar cells has been studied by different research groups [27–29] but the light-induced degradation effect of amorphous silicon (a-Si:H) has been observed by Staebler and Wronski [30] which leads to decreased efficiency of cell with the increase of light exposure, and still it is a crucial problem for amorphous silicon solar cell. So there is a need to investigate the stability in efficiency of amorphous silicon solar cells for practical operation part but in theoretical study temperature coefficient is the only measure to predict how stable the cell efficiency is. Figure 4 shows that the temperature coefficient of the simulated single-junction amorphous silicon solar cell is $-0.23\%/^{\circ}\text{C}$ which will be better in stability of efficiency for practical operation.

3. Fabrication of the Optimized a-Si:H Single-Junction Thin-Film Solar Cells

The designed and optimized a-SiC:H/a-SiC:H-buffer/a-Si:H/a-Si:H single-junction thin-film solar cells have been fabricated for high efficiency by using PECVD. The p-i-n amorphous silicon solar cells with an area of 0.086 cm^2

TABLE 3: a-Si:H films deposition parameters.

Layer	Material	PECVD	Flow rate (sccm)					Pressure (Pa)	Power density (mW/cm ²)	Sub. temp. (°C)	Thickness (nm)
			SiH ₄	MMS	H ₂	B ₂ H ₆	PH ₃				
p	a-SiC:H	RF	6	4	140	10	—	70	130	200	18
Buffer	a-SiC:H	RF	6	4	140	—	—	70	130	200	2
i	a-Si:H	VHF	5	—	45	—	—	50	130	200	500
n	a-Si:H	RF	5	—	—	—	2.5	50	80	200	20

MMS: monomethylsilane.
B₂H₆ and PH₃ : 1% H₂ diluted.

TABLE 4: ZnO films deposition parameters.

Layer	Flow rate (mmol/min)			Pressure	Heater temp. (°C)	Time (hour)	Thickness (nm)
	H ₂ O	DEZ	B ₂ H ₆				
ZnO:B	200	70	0.54	3 Torr	158	4.0	70

DEZ: diethylzinc.

TABLE 5: p-i-n a-Si:H solar cells performance.

Sample ID number	V _{oc} (V)	J _{sc} (mA/cm ²)	FF	Eff. (%)
110308-2-A01	0.881	15.16	0.734	9.81
110308-2-A02	0.884	15.43	0.729	9.95
110308-2-A03	0.884	15.50	0.728	9.98
110308-2-A04	0.884	15.42	0.727	9.91
110308-2-A05	0.881	15.10	0.730	9.72
110308-2-A06	0.876	15.25	0.734	9.81
110308-2-A07	0.880	15.46	0.731	9.95
110308-2-A08	0.881	15.57	0.730	10.02
110308-2-A09	0.882	15.45	0.731	9.96
110308-2-A10	0.878	15.03	0.737	9.74
Average	0.881	15.34	0.731	9.88

have been fabricated on top of the SnO₂:F coated glass (Asahi U-type glass) substrates. The structure of the fabricated cells is glass/SnO₂:F/p-p-a-SiC:H (18 nm)/p-graded-buffer (2 nm)/i-a-Si:H (500 nm)/n-a-Si:H (20 nm)/ZnO:B (70 nm)/Ag (60 nm)/Al (200 nm), which is shown in Figure 1. The deposition sequence started from front TCO SnO₂:F on Asahi U-type glass, which is commercially available in market. The doped layers (p- and n-layers) have been deposited using 13.65 MHz RF-PECVD. The low hydrogen-diluted boron (B) graded bandgap p-a-SiC:H (LD-graded p-a-SiC:H) is formed by the sudden stoppage of the mass flow controller for the B source, that is, B₂H₆, during the deposition of the p-a-SiC:H window layer with RF-PECVD. Intrinsic a-Si:H films have been prepared using a capacitively coupled parallel plate VHF-PECVD system at a substrate temperature of around 200°C. The plasma-excitation frequency of the system has been set at 60 MHz. The MMS flow rates were 4 sccm, whereas the H₂ flow rates can be changed from 45 to 140 sccm. ZnO:B has been deposited using MOCVD technique. When a-Si:H

FIGURE 5: Photo- and dark I - V characteristics of the p-i-n solar cell.

layer deposition has been completed, the samples have been removed from the PECVD. And final contact of Ag/Al has been completed by thermal evaporation. Tables 3 and 4 show the deposition parameters for various layers. In this process, ten single-junction a-Si:H solar cells have been fabricated, and the result is presented in Table 5.

3.1. Solar Cell Performance of Optimized Structure. Both photo- and dark I - V characteristics for the fabricated solar cell have been measured at 25°C under 1-sun (AM 1.5, 100 mW/cm²) solar simulator as shown in Figure 5. Among the ten series of cells, the best initial conversion efficiency of 10.02% has been found with $V_{oc} = 0.88$ V, $J_{sc} = 15.57$ mA/cm², and $FF = 0.73$ for a cell area of 0.086 cm². This initial efficiency is one of the highest recorded results to date for single-junction a-Si solar cells. The other recorded highest initial efficiencies of 10.1% [2], 9.99% [31], and

FIGURE 6: Quantum efficiency curve with wavelength in the range of 300–800 nm.

9.3% [32] have been found by different research groups. However, in this case, the validation of design optimization from numerical analysis has been proved to some extent.

The quantum efficiency (QE) measurement for p-i-n single-junction a-Si:H solar cell has been performed to evaluate the spectral response as shown in Figure 6. The QE curve shows that the cell has a good spectral response in the wavelength range of 400 nm–650 nm and yields an AM1.5G integrated current density J_{sc} of 15.6 mA/cm² over the wavelength region from 300 nm to 800 nm, which also promotes this to be a good candidate as a middle cell in triple-junction structure.

4. Conclusion

The single-junction a-Si:H solar cell has been designed numerically and finally fabricated to investigate the design validation for higher efficiency. The best efficiency of the numerically designed a-Si:H solar cell is 19.62% for i-layer thickness of 500 nm after optimizing the cell parameters. The temperature gradient for a-Si:H has been observed as $-0.23\%/^{\circ}\text{C}$. The optimum bandgap for a-Si:H has been found to be 1.75 eV. The designed and optimized a-SiC:H/a-SiC:H-buffer/a-Si:H/a-Si:H single-junction thin-film solar cells have been fabricated by PECVD. Among the series of ten single-junction a-Si:H cells, the best cell has an initial efficiency of 10.02% with $V_{oc} = 0.88\text{ V}$, $J_{sc} = 15.57\text{ mA/cm}^2$, and $\text{FF} = 0.73$ (area 0.086 cm^2). This initial efficiency is one of the highest recorded results to date for single-junction a-Si solar cells. The QE curve shows that this cell has a good spectral response in the wavelength range of 400 nm–650 nm which means that it would be a good candidate as a middle component cell in triple-junction structure. All in all, the concept of numerical design prior to practical fabrication possesses the validation to a substantial extent toward achieving higher efficiency.

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