IMPROVING THE PERFORMANCE OF HYDROGENATED AMORPHOUS SILICON SOLAR CELL USING a-SiGe:H ALLOY

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The hydrogenated amorphous silicon alloy is expected to play a crucial role in improvement the performance and the stability of a-Si:H solar cells. In this work, a simulation study on the performance of solar cell based on a-Si:H by using a-Si:H alloys, in particular, amorphous silicon-germanium (a-SiGe:H) alloy, is reported. Firstly, we studied the influence of a-SiC:H buffer layer on solar cell performance, and then we are simulated a-SiGe:H absorber layer for enhancing the performance of single junction a-Si:H solar cell. The simulation result shows that the using of a-SiC:H as buffer layer reduce the band gap offset and minimize the recombination of photo-generation carriers at p/i region. The simultaneous optimization of a-SiC:H buffer layer and a-SiGe:H absorber layer has been attributed to the beneficial effect on fill factor FF and J_{SC} without any big loss in open circuit voltage V_{OC}. The maximum efficiency of 13.12 % has been achieved with an absorber layer bandgap of 1.66 eV and thickness of 700 nm for single junction solar cell.

1. Introduction

In recent years, Hydrogenated amorphous silicon (a-Si:H) and its alloys become a promising semiconductors for photovoltaic devices. The conversion efficiency of a-Si:H solar cells has progressed to exceeded 10% for single junction, 13% for tandem junction and 14% triple junction [1]. However, the main disadvantage of a-Si:H solar cell is still the low conversion efficiency compared to others PV technologies, this problem is due to the high defects concentration in a-Si:H material and the degradation of efficiency which is caused the increasing number of metastable defect in solar cell during light soaking or Straeber-Wronski Effect (SWE).

The using of a-Si:H alloys (a-SiC:H, a-SiGe:H...etc) provide a good solution to enhance a-Si:H solar cell performance. The two amorphous silicon-based alloys that are used most in devices are amorphous silicon-germanium (a-SiGe:H) and amorphous silicon-carbon (a-SiC:H). The wide band gap of a-SiC:H alloy used as window layer for minimizing the optical loss, whereas the narrow band gap of a-SiGe:H is used as absorber layer to improving the spectrum response. Therefore, both a-SiC:H and a-SiGe:H are expected to play a crucial role in improvement the performance and the stability of solar cell based a-Si:H.

In last decade, Hydrogenated amorphous silicon germanium (a-SiGe:H) alloy has been researched mainly as a narrow bandgap absorber for improving the solar spectrum response at a long wavelength and the stability of solar cell based a-Si:H [2]. In this paper, different combination of a-SiC:H and a-SiGe:H alloys in p-i-n single junction solar cell, has been studied. This structure aims to explore the proprieties of each a-Si:H alloys, especially a-SiGe:H alloy to enhance the performance of solar cell.

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2. Optoelectronic proprieties of a-SiGe:H alloys.

The a-SiGe:H film is prepared from a gas mixture of SiH_4, GeH_4, and H_2, which is fabricated with several deposition techniques, usually, with RF Plasma enhanced chemical vapor deposition (PECVD) or Hot wire chemical vapor deposition (HWCVD). Compared to PECVD, HWCVD is a feasible option for thin-film solar cell based on amorphous silicon-germanium a-SiGe:H alloy [3]. The proprieties of a-SiGe:H have been depended on not only germanium content (C_{Ge}) but also on hydrogen content (C_H) and its bonding configurations. Indeed, both the optical band gap value (E_{opt}) and electronic proprieties of a-SiGe:H is varied as a function of C_{Ge} and C_H ratio. Another critical parameter for characterizing a-SiGe:H film is hydrogen dilution, which is determined by:

$$R = \frac{[H_2]}{[SiH_2]+[GeH_2]} \tag{1}$$

The hydrogen content (C_H) is:

$$C_H = \frac{[H_2]}{[Si]+[Ge]} \tag{2}$$

Generally, the germanium content can be determined with methods such as Rutherford backscattering spectroscopy (RBS) and X-ray photoelectron spectroscopy (XPS). The germanium content can be expressed as:

$$C_{Ge} = \frac{[Ge]}{[Si]+[Ge]} \tag{3}$$

The combinations of germanium content (C_{Ge}) and hydrogen content (C_H) in films must be carefully varied for controlling the optical gap (E_{opt}) value as function of $[SiH_2]/[GeH_2]$ flow ratio. Akira Terakawa et al in [2] have approximated the E_{opt} as function of C_H and C_{Ge}.

$$E_{opt} = 1.3xC_H - 0.6xC_{Ge} + 1.4(eV) \tag{4}$$

The optical band gap (Eg) of the a-SiGe:H film can be tailored from 1.7 eV to 1 eV by varying the germanium molar fraction. Table 1 represent a comparison of a-SiGe:H alloy and a-Si:H for solar cell applications.

Table 1. Comparison of a-SiGe:H alloy and a-*Si:H for solar cell applications [3,4,5,6, 7].*

	a-Si:H	a-SiGe:H
Bandgab [eV]	1.7-1.8	1.0-1.7
Urbach Energy [meV]	42-50	>45
Photoconductivity [s/cm]	10^{-4} to 10^{-5}	10^{-5} to 10^{-7}
Light-induced degradation (after 1000 hours) [%]	15-30	10-20

By varying the Ge content in the material, the optical bandgap (Eg) can be modulated from 1.7eV to 1.0eV. According to [3, 8, 9], When Eg decreases, The photo-conductivity, Electron and hole mobility decreased, as well as Electron mobility lifetime and hole mobility lifetime product. In contrast; the dark conductivity, the Urbach energy, and Midgap defect density of states increased. Although, a-SiGe:H has poorer electrical properties than that of a-Si:H, the a-SiGe:H has a higher photo-conductivity in comparison to the a-Si:H. thus, it is expected that the a-SiGe:H can show better short circuit current density than that of the a-Si:H based solar cell due to their increased absorption capacity that leads to a reduction of the required absorber thickness [4]. We can determine the optical absorption coefficient of a-SiGe:H film by using the Tauc formula [10], which is expressed as:

$$\alpha = \beta^2 \left[\frac{h\nu - E_g}{h\nu} \right] \qquad (5)$$

The β is constant based on the experiment and their values are 943.51 and 890.58 cm$^{1/2}$ eV$^{1/2}$, for a-Si:H and a-SiGe:H respectively [3, 10]. Taking into account the β values and the law bandgap E_g of a-SiGe:H, the amorphous silicon-germanium has higher absorption coefficient in the visible spectrum than amorphous silicon.

3. Design and Simulation

3.1. Characterization of a-SiGe:H alloy for solar cell.

Hydrogenated amorphous silicon-germanium (a-SiGe:H) is a semiconductor that can be used as low-band gap material in thin-film silicon based solar cells. The direct nature of its band gap, its narrow gap, and its high mobility make a-SiGe:H a good candidate material for the use as absorber layer compared to others a-Si:H alloys like a-SiC:H, a-SiO:H. Although, the high defect density of low-band gap a-SiGe:H films [2-3], the narrow band gap of a-SiGe:H can play a crucial role in improving the performance of solar cells based a-Si:H. Many studies [3, 11] have investigated the a-SiGe:H alloy as absorber layer for single-junction solar cell and confirmed the relation between the characteristics of solar cell and the a-SiGe:H film proprieties. Moreover, The conductivity of doped a-SiGe:H is crucial factor in determining the nature of electrical contacts to the material. The critical factor limiting the performance of doped layers in amorphous silicon alloys is the poor efficiency of doping in these materials therefore, the performance of a-Si:H solar cells could be improved significantly with the development of high quality p- and n-layers.

3.2. Solar cell structure

Our approach is based on using a-Si:H alloys for improving the a-Si:H solar cell performance. In a-Si:H, the hole mobility is much smaller than the electron mobility. Therefore, the *p/i* junction is the dominant junction in a *p-i-n* solar cell structure and the light should enter the solar cell through the p layer instead of the n layer [12]. This work focuses on optimization of p-i-n solar cell by optimizing the thicknesses and bandgap of the a-SiC:H as buffer-layer and a-SiGe:H as absorber layer.
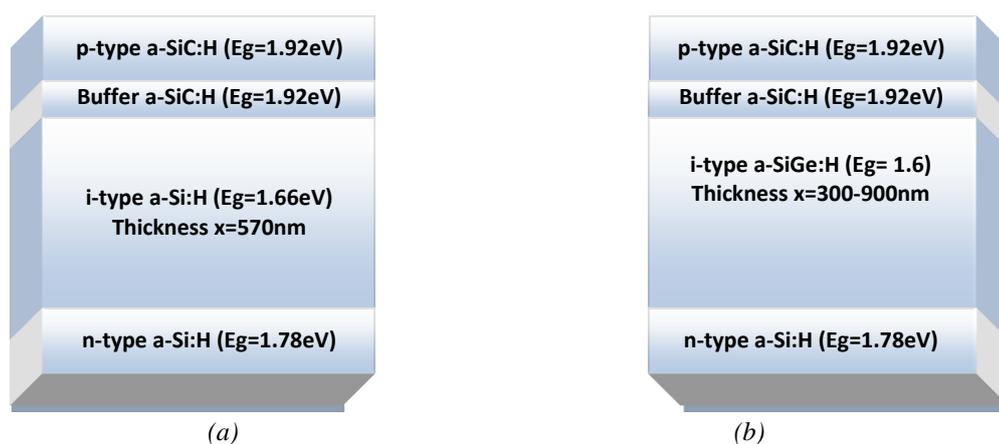

Fig. 1. Structure of p-i-n single-junction solar cell based on a-Si:H alloys: (a) a-SiC:H as p and buffer layer, (b) a-SiGe:H as i-layer.

For simulation, we used the simulation tool wxAMPS (Analysis of Microelectronic and Photonic Structures) that is a well-known solar cell simulation tool developed by Fonash et al. at the Pennsylvania State University. wxAMPS is a powerful program for analyzing and designing thin

film solar cell, particularly well adapted to simulating amorphous silicon solar cells with large densities of point defects in the energy gap [9]. Our model shown in figure 1, depend on amorphous silicon-carbon (a-SiC:H) and amorphous silicon- germanium (a-SiGe:H) to design and optimize the p-i-n single-junction solar cell structures. The input set used in our simulation is reported in Table 2.

Table 2. Input data for simulation of a-Si:H alloys single-junction solar cell. [3-10].

Parameters	p-a-SiC:H	i-a-SiC:H	i-a-SiGe:H	n-a-Si:H
Band gap, E_g [eV]	1.92	1.92	1.66	1.82
Electron affinity, χ[eV]	3.95	3.95	4	3.9
Relative permittivity, ε	11.9	11.9	14	11.9
Effective conduction band density, N_C [cm^{-3}]	2.5×10^{20}	1×10^{20}	3×10^{20}	2.5×10^{20}
Effective valence band density, N_V [cm^{-3}]	2.5×10^{20}	1×10^{20}	1.4×10^{20}	2.5×10^{20}
Electron mobility, μ_e [cm^2/V.s]	20	20	20	20
Hole mobility, μ_h [cm^2/V.s]	2	2	2	2
Characteristic energy of the donor-like tail states, E_{CB} [eV]	0.025	0.025	0.040	0.025
Characteristic energy of the acceptor-like tail states, E_{VB} [eV]	0.049	0.049	0.050	0.049
Gaussian density for donor and acceptor states, N_{DG}&N_{AG} [cm^{-3}]	1×10^{17}	1×10^{17}	1×10^{16}	1×10^{17}
Activation energy, E_a [eV]	0.06	0.06	0.28	0.5
Capture cross-section for donor states, σ_d [cm^2]	$1 \times 10^{-15}/$ 1×10^{-17}	$1 \times 10^{-15}/$ 1×10^{-17}	$1 \times 10^{-15}/$ 1×10^{-17}	$1 \times 10^{-15}/$ 1×10^{-17}
Capture cross-section for acceptor states, σ_a [cm^2]	$1 \times 10^{-17}/$ 1×10^{-15}	$1 \times 10^{-17}/$ 1×10^{-15}	$1 \times 10^{-17}/$ 1×10^{-15}	$1 \times 10^{-17}/$ 1×10^{-15}
exponential prefactor of acceptor-like tail states G_{DO} [cm^{-1}eV^{-1}]	1×10^{21}	1×10^{21}	5×10^{19}	1×10^{21}
exponential prefactor of acceptor-like tail states G_{AO} [cm^{-1}eV^{-1}]	1×10^{20}	1×10^{20}	5×10^{19}	1×10^{21}

4. Results and discussion

4.1 Influence of a-SiC:H Buffer layer

The using of wide band gap a-SiC:H as window layer is important to enhance the absorption in p-i-n solar cell based a-Si:H, due to their high conductivity, low defect density, and wide optical band gap. On the other hand, the insertion of non-doped a-SiC:H at the p/i interface can play a crucial role in improvement the p/i interface of p-i-n solar cell and reduction the recombination at p/i region. So, we focused in this section on a-SiC:H buffer layer at the p/i interface in order to improve the performance of p-i-n solar cells based on a-Si:H.

The optimization of *a*-SiC:H buffer layer depends on their optoelectronic priorities and thickness. In order to optimize the effect of buffer layer on the solar cell performance, we tried to exhibits the effect of thickness variation on solar cell parameters (Fig. 2).

A buffer layer (a-SixC,-x, *0 < x < 1*) was inserted between the p-layer and i-layer to enhance the characteristics of the interface.

Simulations show that a p-i interface layer reduces the concentration of electrons at the p-i interface. As a result the recombination rate at the p-i interface, which limits the *Voc*, is reduced and thus the open-circuit voltage is increased. In the case of an a-Si cell with a p/i buffer layer, however, the loss due to the p/i interface recombination is negligible , which means that the

influence of p/i interface defects can be avoided successfully with the buffer layer and that it does not limit the cell performance.[13-16].

The increasing a-SiC:H buffer-layer thickness V_{OC} and Jsc were almost constant while the fill factor and efficiency were decreased, where we notice a slight degradation. We note that 2 nm is optimum value for a-SiC:H buffer layer thickness.
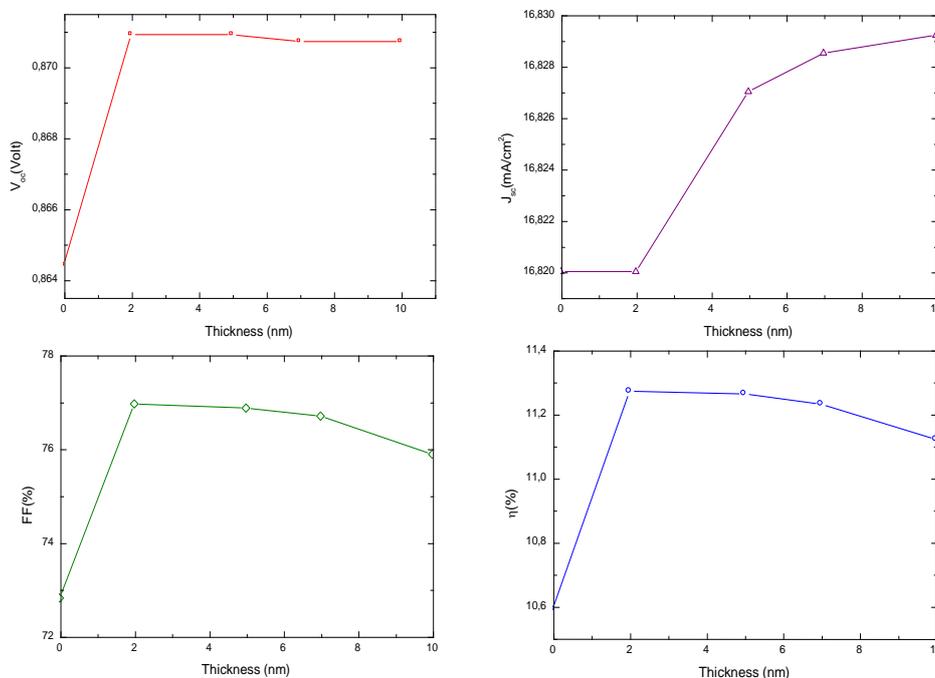

Fig. 2. Variation of photovoltaic characteristics of a single junction pin a-Si:H solar cell device as a function of a-SiC:H Buffer layer thickness

4.2. Optimizing the a-SiGe:H absorber Layer

In this section, we proposed to replace the a-Si:H as absorber layer with the a-SiGe:H film for p-i-n single-junction solar cell. As mentioned above, the a-SiGe:H film was achieved by adding GeH4 to SiH4 gases. To optimize the intrinsic layer, both the germanium content (C_{Ge}) and the hydrogen dilution can be calculated from the measured optical band gap using equation 01 and 04 respectively. Fig. 1.b shows a structure of solar cell with a-SiGe:H absorber layer.

As shown in Fig. 3, the thickness of absorber layer plays a crucial role in improvement of solar cell efficiency. Fig. 3.a shows the open circuit voltage, Voc decreases with the increase of the intrinsic layer, which reflects the relationship between the electrical field and voltage. In Fig. 3.b we find that the short-circuit current is high because of the optical gap of a-SiGe:H is smaller than that of a-Si:H.There is more of absorbed photons so more pairs collected which explains a high current[15]. The short circuit current density (Jsc) increase as a function of a-SiGe:H i-layer thickness to reach 20.69mA/cm^2 for thickness of 720nm.

Fig. 3.c shows the variation of the fill factor. We see a clear decrease of the FF beyond a thickness of 300nm. The FF takes into account the percentage of pairs collected relative to the created pairs. We can say that the a-SiGe:H presents many defects so many trapped pairs and fewer pairs collected. So more the thickness increases in a-SiGe:H, the recombination become more important. On the other hand, the series resistance increases with the increase of the intrinsic layer thickness which decreases the fill factor.

As a result, the highest efficiency has been observed at 700 nm of absorber layer thickness which corresponds to the maximum efficiency of 13.12 % and then a significant drop in efficiency is due to the decline in V_{OC} and FF when the thickness is over 800nm.
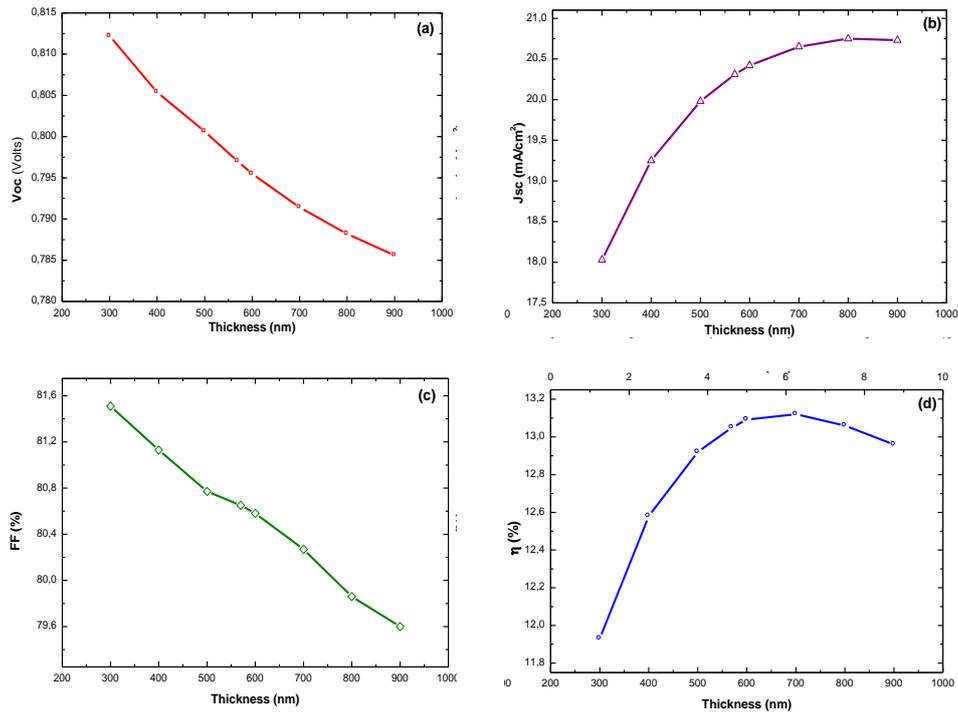
Fig. 3. Photovoltaic parameters of solar cell as a function of a-SiGe:H absorber layer thickness. a- *Open circuit voltage V_{OC},* b- *short circuit current density (J_{sc}),* c- *fill factor (FF), and* d- *efficiency (η).*

4.3. J–V characteristics of solar cell

The main problem of solar cell based on a-Si:H is low fill factor FF owning to the low hole collection of a-Si:H material, and the interface recombination near p/i and i/n region. On one hand, we proposed an approach based on a-SiC:H alloy as buffer layer at the p/i interface for diminishing the band gap discontinuity and interface recombination near p/i region. On the other hand, we introduce the a-SiGe:H as absorber layer to enhance the solar cell parameters. This structure enhances the absorption of the short wavelength light in the p/i front region.

Fig. 4 shows I-V characteristic of solar cell as a function of different structure. The results indicated a clear increase in the overall performance of p-aSiC/buffer-aSiC/i-aSiGe/n-aSi structure. Hence, using a-SiC:H as buffer layer can be enhanced V_{OC} and FF while using a-SiGe:H as absorber layer can be enhanced the output parameter of solar cell.
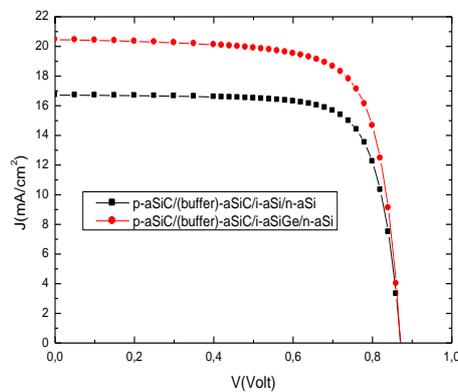

Fig.4. Simulated J–V characteristics of solar cells.

Table 3 listed the development of p-i-n solar cell structure based a-Si:H, the maximum efficiency of 13.12% has been achieved with an absorber layer bandgap of 1.66eV and thickness of 700nm for single junction solar cell. This highest efficiency is achieved due to the enhancement of FF and J_{SC}, whereas a gradual decrease in V_{OC} has marked. Comparing to other simulation and experimental realization [6, 17, 18], one notes that p-aSiC/buffer-aSiC/i-aSiGe/n-aSi structure has achieved the highest efficiency.

Table 3. Comparison the results obtained with the different experimental and simulation results of single-junction p-i-n solar cell based a-Si:H.

Structure	V_{OC}(V)	J_{SC} (mA/cm^2)	FF (%)	η(%)
p-aSi/i-aSi/n-aSi [6]	0.7674	14.99	61.78	7.109
p-aSiC/(buffer)-aSiC/i-aSi/n-aSi [17]	0.844	17.490	72.3	10.68
p-aSiC/(buffer)-aSiC/i-aSi/n-aSi [18]	0.896	18.71	66	10.99
p-aSiC/(buffer)-aSiC/i-aSi/n-aSi	0.8709	16.71	76.10	11.08
p-aSiC/(buffer)-aSiC/i-aSiGe/n-aSi	0.7955	20.65	80.87	13.12

5. Conclusions

In this work, we have carried out systematic studies on single junction solar cell based on a-Si:H. In the first, p-a-SiC:H/i-a-Si:H/n-a-Si:H solar cell structure with a-SiC:H buffer layer at p/i were simulated and optimized. In the second, a simultaneous optimization of a-SiC:H as buffer layer and a-SiGe:H as absorber layer was performed in order to achieve a high solar cells efficiency. The simulation results show that the a-Si:H based solar cell performance have been improved by using a-SiGe:H as absorber layer, particularly FF, and J_{SC}. On the other hand, the solar cell parameter is expected to have a further improvement by optimizing the thickness of a-SiC:H buffer layer and a-SiGe:H absorber layer. The optimization of a-SiGe:H band gap can be attributed to the beneficial effect on the overall performance of solar cell, in particular the fill factor FF and J_{SC} without any big loss in open circuit voltage V_{OC}.

Acknowledgement

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