Journal of Fundamental and Applied Sciences

ISSN 1112-9867

Available online at http://www.jfas.info

Special Issue

In celebrating the 10th anniversary of JFAS

EFFECT OF WIDE-BANDGAP OF N-TYPE AMORPHOUS SILICON OXIDE (a-SiO$_X$:H) LAYER ON THE PERFORMANCE OF a-Si:H SOLAR CELL

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Received: 06 October 2019/ Accepted: 17 November 2019 / Published online: 01 January 2020

ABSTRACT

In p-i-n a-Si:H solar cells, the different optical and electrical losses can be limited by using the wide bandgap a-Si:H alloys as doped layers. This study aims to explore the optoelectronic proprieties of hydrogenated amorphous silicon oxide (a-SiOx:H) for minimizing the optical and electrical losses in solar cell-based a-Si:H, in particular at n/i region. In this context, wxAMPS simulator is used to optimize the properties of the different layers of a-Si:H solar cell, especially n-type layer. The developed a-SiO:H has high photosensitivity and high band gap of 1.95eV, which contributed to attain remarkable fill factor (FF) and high open circuit voltage (V_{OC}). As a result, an efficiency of 12.28 [%] was achieved. Even though, the short circuit courant Jsc is decreased, the high photosensitivity and wide band gap of a-SiOx:H n-layer offered a high V_{OC} of 0.97V. In addition, the efficiency could be improved up to 12.3% by inserting a very thin non-doped a-SiOx:H at n/i interfaces, which offers better short circuit currents in the solar cell.

Keywords : Amorphous silicon oxide; n-type layer; Wide band gap; high open circuit voltage (V_{OC}).

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doi: http://dx.doi.org/10.4314/jfas.v12i1S.6

1. INTRODUCTION

Amorphous silicon (a-Si:H) become an interesting semiconductors for photovoltaic applications due to theirs high optical absorption coefficient, adjustable band-gap (from 1.6 to 1.8 eV) and low temperature of deposition [1]. Moreover, the opto-electronic properties of a-Si:H have been influenced by alloying with others materials like oxygen, carbon, germanium …etc. Alloying a-Si:H with germanium aims to have a narrow band gap. So, the optical bandgap (Eg) can be adjusted from 1.7eV to 1.0eV by increasing the Ge content in the material. In contrast, Alloying with oxygen or carbon could be increased the band gap. Furthermore, the photoluminescence and the line width of a-Si:H alloys increase as a function of optical band gap [1,2].

Several simulations and experimental results have been approved the interrelation between the performances of a-Si:H solar cell and the properties of p- and n-doped layers [3 , 4]. In particular window layer (p-layer), thus any change of the window layer design can be affected significantly the performance of a-Si:H solar cell. But even so, the n-doped layer can be played a crucial role in optimizing the solar cell parameters.

Amorphous silicon and its alloys has been the subject of investigation for more than three decades. Especially, the large band-gap a-Si:H alloys that contain carbon, oxygen or both. The wide band gap material like a-SiO:H is usually considered as window layer for single junction and as absorber materials of top cell for multi-junction. Their properties and applicability in solar cells based on a-Si:H has been studied and confirmed in [1]. In this context, a-SiO:H is an interesting material, hence it can introduce as doped layer for improving the performance of solar cell based on a-Si:H by increasing the built-in potential (Vbi) and minimising the recombination losses at interlayers [5]. Some of studies involving a-SiOx:H confirmed that the photoconductivity of a-SiO:H is important compared to a-SiC:H at similar optical bandgaps [6] . The objective of this work is to use a–SiO:H as n-doped layer in a-Si:H solar cells and try to achieve both a higher JSC and Voc. With simulation study and analysis method, we try to design a n-doped and an ultrathin non doped layer at n/i regions based on a–SiO:H.

2. THEORETICAL MODEL

Recently, considerable studies have grown up around the a-SiO:H alloy and its application in a-Si:H solar cells concepts. These studies have been mainly carried out on wide bandgap (Eg) of the a-SiO:H as window p-layer and better reflective of a-SiO:H as n-layer [6]. Even after several studies reported a-SiO:H film as window-layer, which provides a high Voc for a-Si:H single-junction solar cell, only a few research have been investigated the a-SiOx:H alloy as n-doped layer for a-Si:H solar cell and reported its relation to the solar cell performance. So, the wide-band-gap a-Si:H alloys like a-SiC:H, a-SiO:H is used as a window layer, while n-type layer remains in n-a-Si:H film. The use of a-SiO:H as n-type layer increases the use of light in the absorber layer and reduces the optic losses in the non active regions of the cell [7]. Furthermore, the a-SiO:H layer showed less light-induced degradation (LID) effect in comparison to the a-Si:H. In fact, several experimental and simulations studies reveal a difference in the LID of 5.7 % [3, 8].

2.1 Characterization of n-type a-SiO:H layer

Opto-electrical characteristics optimization of a-SiO:H alloy was challenging because the introduction of oxygen in a-Si:H deteriorate slightly the structure of a-Si:H network and increase the defects density [9]. As much as the oxygen content rise in a-Si:H, some proprieties of the material (film quality and optical absorption) is deteriorated. However, the optical gap and activation energy of n-doped a-SiO:H layer can be enhanced without much deterioration in optoelectronic properties.

Table 1. Comparison of the optical and electrical proprieties of the (n) a-SiO:H layer with the (n)a-Si:H layer [3,8].

n-type layer	Bandgap Eg in eV	Dark conductivity σ_d in S/cm	Activation energy Ea in eV
(n) a-Si:H	1.82	$1.44x10^{-2}$	0.16
(n) a-SiO:H	1.95	$3.72x10^{-4}$	0.30

The large bandgap of a-SiO:H alloy is due to the oxygen content. Moreover, the doping a-Si:H-oxygen-phosphorus reduce the parasitic absorption in (n)a-SiO:H layer compared to (n)a-Si:H layer. In addition to low dark conductivity, the low refractive index of (n)a-SiO:H increase the reflection at interface i/n region. Nevertheless, the oxygen alloy deteriorates the electronic characteristics of (n)a-SiO:H layer as well as the doping efficiency [10].

2.2 Role of Phosphorus-doped layer

Although, some of previous studies involving the use of a-SiO:H as n-doped layer have reported that no improvements are achieved compared to the use of an (n)a-Si:H or (n)µc-Si:H layer [5,10]. The low refractive index of (n)a-SiO:H layer compared to (n)a-Si:H or (n)µc-Si:H layer, increased the reflection between the i- and n-layers. Therefore, the light is mirrored back into the absorber layer. Consequently, the reflection at i/n interface enhances the management of the light in the solar cell.

As mentioned above, the open circuit voltage (Voc) value depend on built-in potential (Vbi) that create into the solar cell. So, any gains in built-in potential (Vbi) led to the gains in Voc and FF. According to [11, 12], the built-in potential Vbi can be enhanced by improving the mobility between absorber layer and n-layer, and the energy barrier between intrinsic layer and n-doped layer. Therefore, it is important to have a high quality buffer layer interlayer, in particular at defective i/n region to reduce the parastic absorption and the bandgap offset. Not only the proprieties of intrinsic layer are important for high Voc and FF but also the band gap and activation energy of the doped layers is essential to enhance the Voc and FF. In this work, we present the influence of the a-SiO:H as n-layer on the solar cell performances. The basic parameters of the solar cell are briefly discussed below.

$$V_{OC} = \frac{nkT}{q} \ln\left(\frac{J_{SC}}{J_0} + 1\right) \qquad (01)$$

In p-i-n structure, both n- and p-layers is considered as an ohmic contact and the intrinsic layer is absorber layer. In this case, the modelling of p-i-n junction, however, is considered as p-n junction crystalline devices modelling. In the same way, the reverse saturation current density (J_O) is similar to p-n diode, whose Jo is described as a function of hole diffusion (Dp) and hole density (p_{no}) in the n-doped layer, as well as electron diffusion (Dn) and electron density (n_{io}) in intrinsic layer :

$$J_O = \frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{io}}{L_n} \qquad (02)$$

In thin film silicon solar cells, both hole diffusion length (Lp) in n-doped layer and electron diffusion length (Ln) in intrinsic layer are smaller. Thus, the high doping concentration of

n-layer compared to i-layer led to $p_{no} << n_{io}$, so, Jo can be written:

$$J_O = \frac{qD_n n_{io}}{L_n} \quad (03)$$

The built-in potential Vbi of the n-i contact is described as following [11, 12].

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{n_{n0}}{n_{i0}}\right) \quad (04)$$

The electron density (n_{io}) in intrinsic layer can be calculated as a function of the electron density (n_{n0}) in n-type layer as following:

$$n_{i0} = n_{n0} \exp\left(\frac{-qV_{bi}}{kT}\right)\} \quad (05)$$

$$J_{O\ell} = \frac{qD_n n_{io}}{L_n} \exp\left(\frac{-qV_{bi}}{kT}\right) \quad (06)$$

As seen in equation (5) and (6), V_{bi} represent the activation energy of J_{oe}. So, from equation (06), we can conclude that the built-in-potential depend on not only the temperature variation but the variation of Fermi level in a-Si:H. In comparison to single crystalline silicon, this variation is limited in the temperature range of 300K - 400K. To evaluate built-in-potential (Vbi), we can also use the equations (01) and (06):

$$V_{OC} = \frac{n_\ell kT}{q}\left(\ln J_{SC} - \ln J_{O\ell}\right)$$

$$V_{OC} = \frac{n_\ell kT}{q}\left(\ln J_{SC} - \ln\left(\frac{D_n}{L_n} n_{n0}\right)\right) + n_\ell V_{bi} \quad (07)$$

From equation (07), we can be concluded that Vbi is equal to Voc/n_l , using Voc, at T = 0, V_{OC}.

3. DESIGN AND SIMULATION

In this work, a simulation study on employing the a-SiO:H alloy as n-doped layer for solar cell based on a-Si:H is carried out. This optimized n-type layer has then been used for enhancing the solar cell performance. According to equations (04) and (07), the high band gap of n-doped a-SiO:H layer can be played a key role to increase the Voc and FF of solar cell based on a-Si:H.

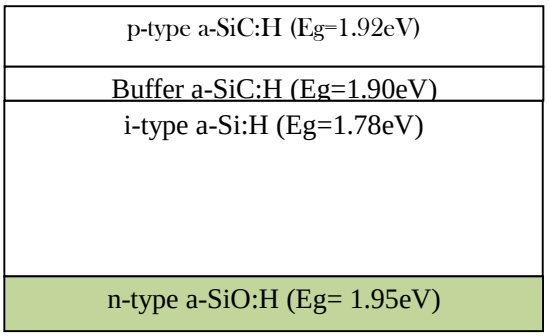

Fig.1. Design of a-Si:H p-i-n solar cell structure with n-type a-SiO:H layer

To optimize the designed structure of a-Si:H-based solar cell, wxAMPS is used as numerical and analytical simulation tool in this work. wxAMPS is numerical simulations code that can help to verify the effect of different parameters of material and structure on the solar cell performance. Fig 1 shows the designed structure which is composed of a p-i-n junction with a-SiOx:H as the alternative for conventional (n)a-Si:H. The parameters of simulation are described in Table 2.

Table 2. Parameters used in the simulation [3, 6, 13].

Parameters	p-aSiC:H	i-aSiC:H	i-aSi:H	i-aSiO:H	n-aSiO:H
Thickness [nm]	10	3	570	5	14
Mobility gap [eV]	1.92	1.90	1.78	1.93	1.95
Electron mobility [cm2/Vs]	20	20	20	9.76	5.46
Hole mobility [cm2/Vs]	2	2	2	3.14	1.82
Doping concentration [/cm3]	$1x10^{19}$	0	0	0	$1x10^{19}$
Effective DOS in CB [/cm3]	$2x10^{20}$	$1x10^{20}$	$1x10^{20}$	$2x10^{20}$	$2x10^{20}$
Effective DOS in VB [/cm3]	$2x10^{20}$	$1x10^{20}$	$1x10^{20}$	$2x10^{20}$	$2x10^{20}$
Dangling bond density of states [/cm3]	$4.01\ x10^{17}$	$4.01\ x10^{17}$	$2.35\ x10^{16}$	$1.65\ x10^{17}$	$3.98\ x10^{17}$

In this study, the a-Si:H solar cell with a-SiO:H as n-type layer were simulated. The basic solar cell performance and the simulation results are evaluated and discussed in the section below.

4. RESULTS AND DISCUSSION

This paper attempts to evaluate the effect of (n)a-SiO:H layer on the solar cell performance. Modeling and analysis has been described numerically that the employing of wide band gap a-SiO:H film as n-doped layer can be enhanced the efficiency of solar cell at the same proprieties of window and intrinsic layers of conventional structure. In fact, the optimization of (n)a-SiO:H layer improve significantly the Voc, FF, and Eff.

4.1 Optimization of n-type a-SiO:H layer

In order to evaluate the effect of the proprieties of n-layer on the solar cell performance, the open circuit voltage Voc, fill factor FF, short circuit current density Jsc, serial resistance Rs and efficiency are simulated as a function of a-SiO:H n-layer characteristics, including the thickness and doping concentration.

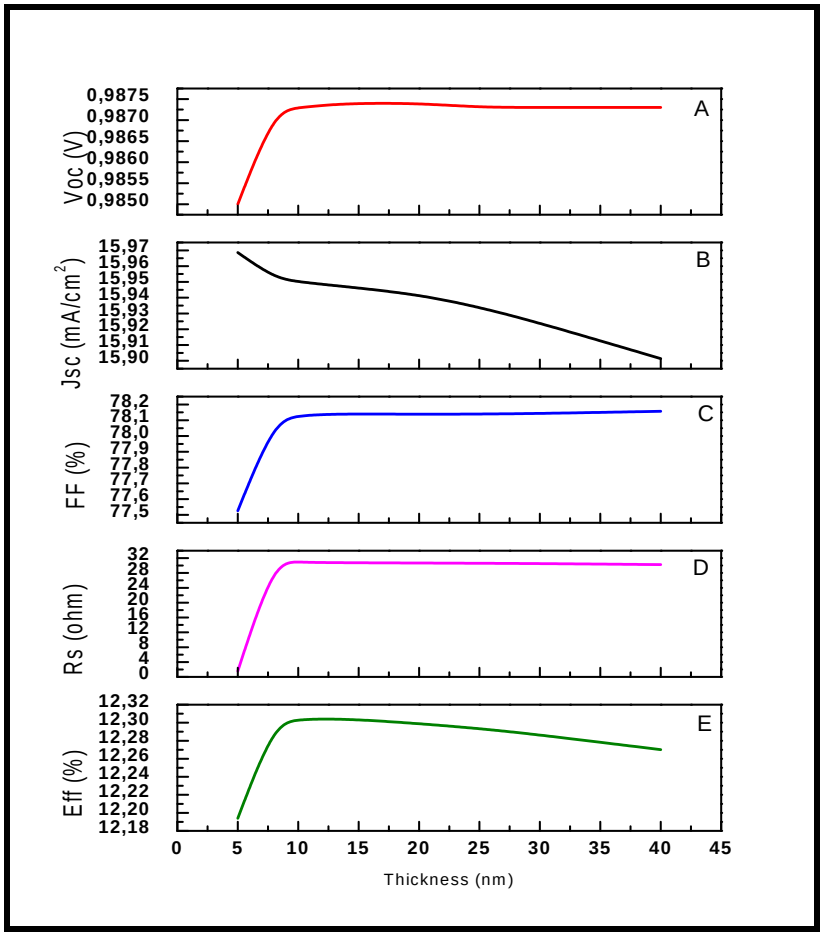

Fig.2. Variation of the parameters of a-Si:H solar cell as a function of a-SiO:H n-layer thickness, (A) Open circuit voltage, (B) short circuit current density, (C) Fill factor, (D) Serie resistance, (E) Efficiency.

The open circuit voltage and fill factor of the solar cell initially increase until achieving its maximum value in the range 10-16nm and then gradually decreases with increasing of (n)a-SiO:H thickness due to the series resistance. As a result, the highest efficiency can be achieved in the range 10-16nm of n-layer thickness. Nevertheless, the short circuit current density decreases as a function of n-layer thickness. Therefore, a significant drop in efficiency has been marked when the thickness is over 16nm. The decline in Jsc is owning to the low electronic properties of the (n)a-SiO:H layer and the ohmic contact of n-layer

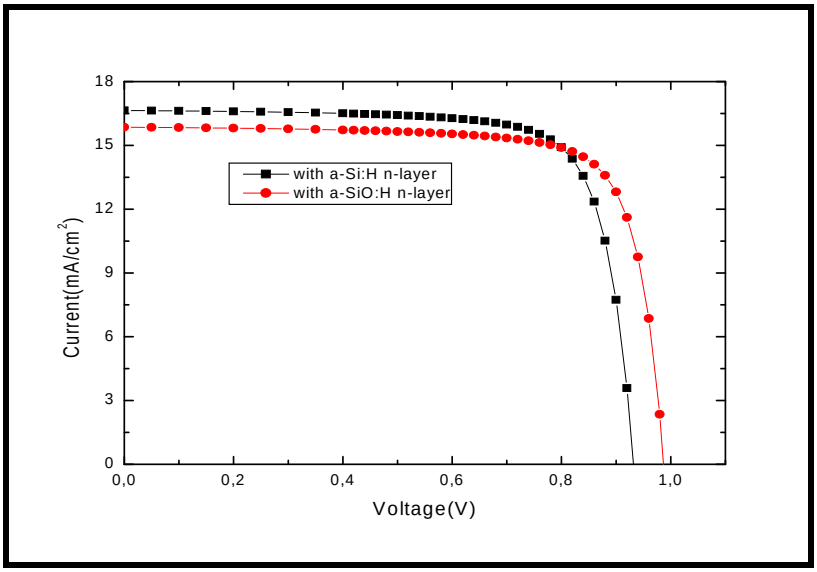

Fig.3. Simulated current-voltage characteristics of single junction a-Si:H solar cell structures.

As shown in fig. 2 and 3, the highest efficiency of the solar cell is obtained when the value of Voc, Jsc, FF and Rs are 0.978 V, 15.93 mA/cm2, and 78.3% and 29.1ohm respectively, for solar cell based on (p)a-SiC:H/(i)a-Si:H/(n)a-SiO:H structure. Thus, the employing a-SiO:H as n-type layer for a-Si:H solar cell was significantly performed compared with other studies that was studied of a-Si:H solar cell with n-type layer in a-Si:H or µ-SiO:H [6 , 9 , 10 , 14]. After a numerical analysis, the optimized efficiency is 12.3% which is the highest efficiency in comparison to a maximum value of the similar solar cell efficiency [15, 16].

4.2 Effect of a-SiO:H buffer layer

The performonce of solar cell not only depends on the absorption in intrinsic layer, but also on charge carriers combination at interface region (p/i and i/n). Therefore, the insertion of non-doped a-SiO:H as buffer layer at i/n region is important to improve the performance of

solar cell due to their low defect density, high conductivity, and wide band gap. In this section, a simultaneous optimization of both buffer and n-layers for a-Si:H solar cell can be carried out further increase the Voc and J_{SC}.

Table 3. Simulated performance of the solar cell with differents n-layer structures.

n-layer	V_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)	Eff. (%)
(n)a-Si:H	0.928	16.64	76.1	11.92
(n)a-SiO:H	0.983	15.83	77.4	12.28
(n)a-SiO:H with buffer	0.979	16.06	78.2	12.33

As shown in table 03, the use of a-SiO:H as buffer layer at i/n region enhances the carrier collection by minimizing the recombination at this region. As result, the JSC has been improved. The gain in JSC is explained by the low parasitic absorption at i/n region and the small refractive index of the (n)a-SiO:H layer compared to the (n)a-Si:H layer [11]. On the other hand, both The VOC and JSC are limited by the band offset and optical absorption losses at i/n interface. Therefore the insertion of wide optical band gap at i/n interface could be increased Jsc [13]. As shown in table 03, the results is demonstrated that the efficiency reaches a maximum value of 12.33% (JSC=16.06mA/cm2; FF=78.2; VOC =0.97V) when the band gap values of n-layer and buffer layer are 1.95 eV, 1.93 eV, respectively.

4. CONCLUSION

In this research, the effect of (n)a-SiO:H layer on the solar cell performance were investigated. The simulation results shows that the use of a-SiO:H film as n-doped layer can improve the open circuit voltage Voc. Furthermore, an effective theoretical analysis and numerical simulation has been done to check the role of wide-bandgap a-SiO:H as n-doped layer in enhancement the fill factor. In addition, the use of a-SiO:H as buffer layer minimize the recombination at n/i region and increase the internal electric field in the solar cell. After optimizing the parameters of n-type a-SiO:H layer including the thickness and doping quality, the efficiency of 12.33% (V_{OC}=0.97 V, J_{SC}=16.06 mA/cm^2, and FF=78.2%) has been achieved for a-Si:H solar cell with a-SiO:H as n-layer.

5. ACKNOWLEDGEMENTS

The authors acknowledge and thank Prof. Rockett, Dr. Yiming Liu and Prof. Stephan Fonash of the Pennsylvania State University for generously sharing the wxAMPS source code.

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How to cite this article:
Idda A, Ayat L, Dahbi N and Zaoui O. Effect of wide-bandgap of n-type amorphous silicon oxide (a-siox:H) layer on the performance of a-Si:H solar cell. J. Fundam. Appl. Sci., 2020, *12(1S), 66-77.*