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Comparative Study of the Influence of μc-Si:H, a-Si:H, pm-Si:H and μc-SiO*x* as a Passivation Layer on the Performance of HIT *n*-c-Si Solar Cells

Z. Dahlal[1], F. Hamdache[1], D. Rached[1], W.L. Rahal[2,3,*]

[1] *Laboratoire de Physique des Plasmas, Matériaux Conducteurs et Leurs Applications, U.S.T.O.M.B. – B.P. 1505, El M'naouar, Oran, Algérie*
[2] *Laboratoire d'Analyse et d'Application des Rayonnements, U.S.T.O.M.B. – B.P. 1505, El M'naouar, Oran, Algérie*
[3] *Département de Physique, Faculté des Sciences Exactes et de l'Informatique, Université Abdelhamid Ibn Badis de Mostaganem, Mostaganem, Algérie*

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One of the most important factors limiting the performance of Hetereojunction with Intrinsic Thin layer (HIT) c-Si solar cells is the defect density on the surface of crystalline silicon. A numerical modelling has been employed in order to choose the most efficient material as a passivation layer in a HIT c-Si solar cell. We have chosen for this study the following materials: hydrogenated microcrystalline silicon μc-Si:H ($Eg_{\text{i-μc-Si:H}} = 1.40$ eV), hydrogenated amorphous silicon a-Si:H ($Eg_{\text{i-a-Si:H}} = 1.84$ eV), hydrogenated polymorphous silicon pm-Si:H ($Eg_{\text{i-pm-Si:H}} = 1.96$ eV) and hydrogenated microcrystalline silicon oxide μc-SiO$_x$:H ($Eg_{\text{i-μc-SiO}x} = 2.5$ eV). The simulation results show that the improvement of the electric field at the emitter with the use of μc-Si:H and a-Si:H as a passivation layer makes the power conversion efficiency of the HIT c-Si to increase from 25.42 to 26.34 %. The creation of a potential barrier for photogenerated holes at i-pm-Si:H/*n*-c-Si and μc-SiO$_x$/*n*-c-Si junctions drops the efficiency from 23.87 to 3.10 %. This barrier prevents the passage of photogenerated holes towards the emitter which leads to a strong recombination rate of electron-hole pairs and therefore to a decrease in power efficiency. With a band gap of 1.84 eV, hydrogenated amorphous silicon a-Si:H is the most appropriate candidate for the elaboration of a passivation layer on the surface of crystalline silicon for this type of solar cells.

Keywords: Solar cells, HIT, Amorphous silicon, Potential barrier, SCAPS-1D, *J*-*V* characteristic.

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1. INTRODUCTION

A HIT (Heterojunction with Intrinsic Thin layer) silicon solar cell was first designed and named by Sanyo Co. Ltd (now Panasonic Co. Ltd) in 1991 [1]. This solar cell is composed of a c-Si silicon wafer as an active layer and ultra-thin amorphous silicon layers as a passivation layer and an emitter. The main advantages of HIT solar cells are their fabrication at low temperature (200 °C), as well as high stable efficiency of crystalline silicon (c-Si) [2-5].

The excellent properties of crystalline silicon allow the HIT solar cell to have an efficiency equal to 26.6 % [6]. Despite the presence of defects in the amorphous matrix, which cause losses affecting the performance of photovoltaic cells (due to the nature of the material gap [7]), materials based on intrinsic hydrogenated amorphous silicon (a-Si:H) are excellent as a passivation layer between an absorber layer (*n*-doped crystalline silicon) and an emitter (*p*-doped hydrogenated amorphous silicon).

In this study, we will compare the quality of surface passivation with several amorphous materials to improve the efficiency of such a solar cell. These materials are: hydrogenated microcrystalline silicon μc-Si:H ($Eg_{\text{i-μc-Si:H}} = 1.40$ eV), hydrogenated amorphous silicon a-Si:H ($Eg_{\text{i-a-Si:H}} = 1.84$ eV), hydrogenated polymorphous silicon pm-Si:H ($Eg_{\text{i-pm-Si:H}} = 1.96$ eV) and hydrogenated microcrystalline silicon oxide μc-SiO$_x$:H ($Eg_{\text{i-μc-SiO}x} = 2.5$ eV) [8, 9].

The results of the numerical modelling are obtained using solar cell capacitance simulator SCAPS-1D.

2. INPUT PARAMETERS OF THE STUDIED SOLAR CELL

The structure we proposed to study in this work is a HIT *n*-c-Si (ZnO/*p*-μc-Si:H/i-μc-Si:H/*n*-c-Si/n^+-c-Si/Al) solar cell shown in Fig. 1.

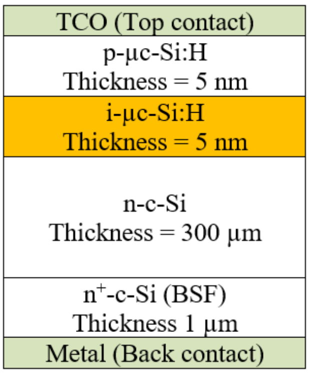

Fig. 1 – Schematic diagram of a HIT *n*-c-Si solar cell

The 300-micron thick *n*-doped c-Si substrate acts as an absorber. Although it is possible to make HIT cells on a *p*-type substrate [10], we have focused in this article on HIT cells on an *n*-type substrate. At the top of the device, we have chosen zinc oxide (ZnO) with a work function equal to 5.2 eV as a transparent conduct-

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[*] leila.rahal@univ-mosta.dz

ing oxide [11]. At the back of the cell, we have used aluminum as a metal with a work function equal to 3.9 eV [12]. The emitter consists of *p*-doped hydrogenated microcrystalline silicon (μc-Si:H). The addition of an intrinsic μc-Si:H layer to the c-Si surface is essential. Without this passivation layer, the concentration of recombination centers is so high that the generated electron-hole pairs (EHP) in the absorber recombine before being extracted from the cell. The parameters used in our simulations are grouped in Table 1 [8, 9].

Table 1 – Principal input parameters of the HIT *n*-c-Si solar cell

Parameters	Units	*p*-μc-Si:H	i-μc-Si:H	i-a-Si:H	i-pm-Si:H	i-μc-SiO$_x$	*n*-c-Si	n^+-c-Si (BSF)
d	μm	0.005	0.005	0.005	0.005	0.005	300	1
E_μ	eV	1.40	1.40	1.84	1.96	2.50	1.12	1.12
χ	eV	4	4	4	3.95	3.67	4.22	4.22
N_C, N_V	cm^{-3}	2.10^{20}	2.10^{20}	2.10^{20}	2.10^{20}	2.10^{20}	10^{19}	10^{19}
μ_n	cm^2/Vs	32	32	20	20	32	1450	1450
μ_p	cm^2/Vs	8	8	4	12	8	450	450
N_D	cm^{-3}	0	0	0	0	0	10^{17}	10^{21}
N_A	cm^{-3}	10^{19}	0	0	0	0	0	0
Nt	cm^{-3}	10^{21}	10^{14}	10^{14}	10^{14}	10^{14}	10^{10}	10^{10}

To compare the quality of the passivation layer of such a solar cell, we have used various materials. The parameters used for the structure as well as materials as a passivation layer (a-Si:H, pm-Si:H and μc-SiO$_x$) are based on the values taken from the literature [8, 9].

3. SIMULATION MODEL

To accomplish our study, we used the SCAPS one-dimensional numerical simulation software (Solar Cell Capacitance Simulator) [13-15]. Developed by the Department of Electronic and Computer Systems (ELIS) at the University of Gent in Belgium, SCAPS-1D was originally designed for the CIS, CdTe and CIGS family cells. However, a number of extensions have been developed to become applicable to crystalline c-Si and amorphous a-Si:H solar cells.

SCAPS-1D simultaneously solves the Poisson equation (Eq. (3.1)) and the continuity equations for free electrons and free holes (Eq. (3.2) and Eq. (3.3)) using finite differences and the Newton-Raphson method [16]

$$\frac{\partial^2\Psi(\mathrm{x})}{\partial x^2} = -\frac{\rho(x)}{\varepsilon}, \tag{3.1}$$

$$G(x) - R\big(p(x),n(x)\big) \boxminus \frac{1}{q}\frac{\partial j_{n(x)}}{\partial x} = 0, \tag{3.2}$$

$$G(x) - R\big(p(x),n(x)\big) \boxminus \frac{1}{q}\frac{\partial j_{p(x)}}{\partial x} = 0, \tag{3.3}$$

where $\Psi(x)$ is the electrostatic potential, $\rho(x)$ is the space charge density in the semiconductor, $\varepsilon(x)$ is the dielectric permittivity of the semiconductor, $J_n(x)$ is the electron current, $J_p(x)$ is the hole current, q is the electron charge, $G(x)$ is the net optical generation of free electron-hole pairs per unit volume, $R(x)$ is the net recombination of free carriers per unit volume.

4. RESULTS AND DISCUSSION

Under illumination AM 1.5 and at a temperature of 25 °C, we obtained for a HIT *n*-c-Si composed of μc-Si:H as a passivation layer ($Eg_{\text{i-μc-Si:H}}$ = 1.40 eV): short-circuit current density J_{sc} = 39.31 mA/cm^2, open-circuit voltage V_{oc} = 0.79 V, Fill Factor FF = 81.26 and efficiency η = 25.41 %. Fig. 2 shows the evolution of the band diagram of this cell.

The results of modeling the current-voltage curves *J-V* at 100 mWcm^{-2} of AM 1.5 light, as a function of μc-Si:H, a-Si:H, pm-Si:H and μc-SiO$_x$ as a passivation layer, are shown in Table 2.

According to Table 2, the efficiencies of cells formed from μc-Si:H and a-Si:H increase from 25.41 to 26.34 %, while for those made up of pm-Si:H and μc-SiO$_x$, the efficiencies drop. They are equal to 23.87 % and 3.10 %, respectively. V_{oc} and J_{sc} follow the same drift as the efficiency η. In fact, V_{oc} goes from 0.82 to 0.79 V and J_{sc} goes from 39.37 to 39.31 mA/cm^2.

For cells made of a material with a wide band gap (i-μc-SiO$_x$), V_{oc} drops to 0.68 V and J_{sc} to 32.12 mA/cm^2.

Fig. 3 shows the electric field variation for i-μc-Si:H, i-a-Si:H, i-pm-Si:H and i-μc-SiO$_x$ materials used as a passivation layer in a HIT *n*-c-Si solar cell. An improvement in this electric field clarifies the increase in η, V_{oc} and J_{sc} for cells made from i-a-Si:H but does not provide information on a decrease in these parameters for cells made from i-pm-Si:H and i-μc-SiO$_x$. We can notice from Fig. 4 a decrease in the recombination rate of EHP created in the active layer (*n*-c-Si). This decrease had a negative impact on the *J-V* characteristic. Indeed, in addition to the fall of V_{oc} and J_{sc}, the FF drops from 81.28 to 14.18 %.

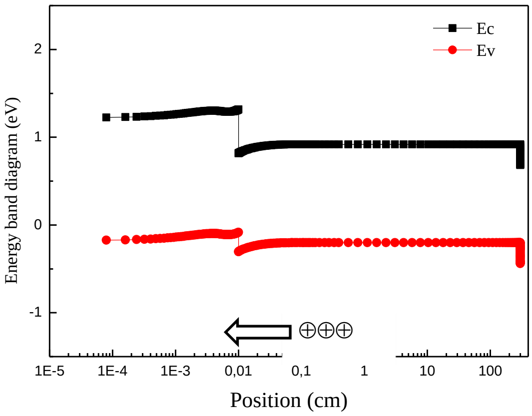

Fig. 2 – Schematic band diagram of a HIT *n*-c-Si solar cell: ZnO/*p*-μc-Si:H/i-μc-Si:H/*n*-c-Si/n^+-c-Si/Al ($Eg_{\text{i-μc-Si:H}}$ = 1.40 eV) under solar illumination

Table 2 – Photovoltaic parameters of a HIT n-c-Si solar cell with μc-Si:H, a-Si:H, pm-Si:H, μc-SiO$_x$ as a passivation layer

	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	η (%)
i-μc-Si:H	0.79	39.31	81.26	25.42
i-a-Si:H	0.82	39.37	80.95	26.34
i-pm-Si:H	0.82	39.21	73.56	23.87
i-μc-SiO$_x$	0.68	32.12	14.18	3.10

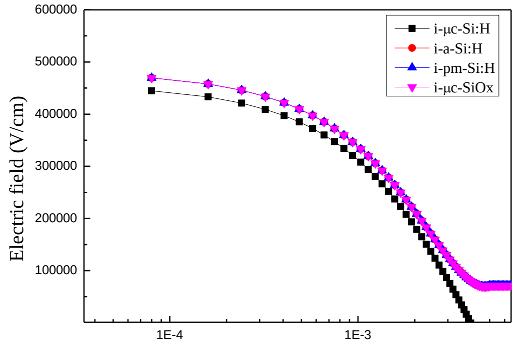

Fig. 3 – The electric field for i-μc-Si:H, i-a-Si:H, i-pm-Si:H and i-μc-SiO$_x$ materials used as a passivation layer in HIT n-c-Si cells as a function of position in the device

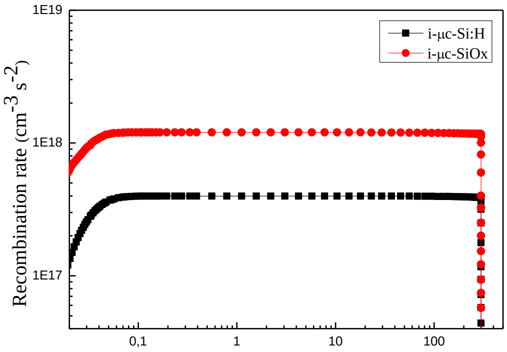

Fig. 4 – Plots of the recombination rate of a HIT n-c-Si solar cell: ZnO/p-μc-Si:H/i-μc-Si:H/n-c-Si/n^+-c-Si/Al and ZnO/p-μc-Si:H/i-μc-SiO$_x$/n-c-Si/n^+-c-Si/Al as a function of position in the device

Following these results, we have plotted the energy band diagram of HIT n-c-Si solar cells for i-μc-Si:H and i-μc-SiO$_x$ materials used as a passivation layer.

We can notice from the schematic energy band diagram under illumination (Fig. 5) the creation of a potential barrier for photogenerated holes at the i-μc-SiO$_x$/n-c-Si junction. This barrier at the level of the valence band will prevent holes from passing to the emitter, which involve a great recombination of EHP and consequently a drop in the efficiency to 3.10 %.

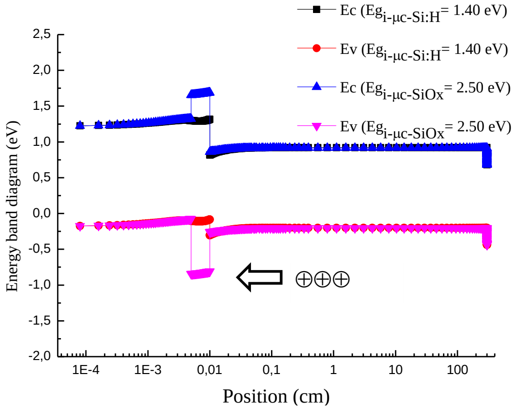

Fig. 5 – Schematic of the energy band diagram of HIT n-c-Si solar cells: ZnO/p-μc-Si:H/i-μc-Si:H/n-c-Si/n^+-c-Si/Al and ZnO/p-μc-Si:H/i-μc-SiO$_x$/n-c-Si/n^+-c-Si/Al under solar illumination

5. CONCLUSIONS

In summary, several materials have been used as a passivation layer in HIT c-Si solar cells. The efficiency of cells with i-μc-Si:H and i-a-Si:H increases from 25.41 to 26.34 %, while for cells made up of i-pm-Si:H and i-μc-SiO$_x$ it drops from 23.87 to 3.10 %, respectively. An improvement in the electric field explains the increase in the J-V characteristic for a cell made from i-a-Si:H. A decrease in the recombination rate of EHP created in the active layer (n-c-Si) had a detrimental effect for cells with a wide band gap as a passivation layer (i-pm-Si:H and i-μc-SiO$_x$). A large μc-SiO$_x$ gap causes the creation of a potential barrier for photogenerated holes at the i-μc-SiO$_x$/n-c-Si junction, thus preventing the passage of holes towards the emitter, which leads to strong recombination of EHP and therefore a decrease in efficiency.

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Порівняльне дослідження впливу μc-Si:H, a-Si:H, pm-Si:H та μc-SiO*x* як пасивуючого шару на продуктивність сонячних елементів HIT *n*-c-Si

Z. Dahlal[1], F. Hamdache[1], D. Rached[1], W.L. Rahal[2,3]

[1] *Laboratoire de Physique des plasmas, Matériaux Conducteurs et leurs Applications,*
U.S.T.O.M.B. – B.P. 1505, El M'naouar, Oran, Algérie
[2] *Laboratoire d'Analyse et d'Application des Rayonnements, U.S.T.O.M.B. – B.P. 1505, El M'naouar, Oran, Algérie*
[3] *Département de Physique, Faculté des Sciences Exactes et de l'Informatique,*
Université Abdelhamid Ibn Badis de Mostaganem, Mostaganem, Algérie

Одним з найважливіших факторів, які обмежують продуктивність сонячних елементів c-Si на основі гетеропереходу з внутрішнім тонким шаром (HIT), є густина дефектів на поверхні кристалічного кремнію. Чисельне моделювання було використано для вибору найбільш ефективного матеріалу як пасивуючого шару в сонячному елементі HIT c-Si. Для дослідження ми вибрали такі матеріали: гідрогенізований мікрокристалічний кремній μc-Si:H ($Eg_{\text{i-μc-Si:H}}$ = 1,40 eV), гідрогенізований аморфний кремній a-Si:H ($Eg_{\text{i-a-Si:H}}$ = 1,84 eV), гідрогенізований поліморфний кремній pm-Si:H ($Eg_{\text{i-pm-Si:H}}$ = 1,96 eV) і гідрогенізований мікрокристалічний оксид кремнію μc-SiO_x:H ($Eg_{\text{i-μc-SiO}x}$ = 2,5 eV). Результати моделювання показують, що посилення електричного поля на випромінювачі з використанням μc-Si:H та a-Si:H як пасивуючого шару призводить до збільшення ефективності перетворення енергії сонячного елементу HIT c-Si з 25,42 до 26,34 %. Створення потенційного бар'єру для фотогенерованих дірок на переходах i-pm-Si:H/*n*-c-Si та μc-SiO_x/*n*-c-Si знижує ефективність з 23,87 до 3,10 %. Цей бар'єр перешкоджає проходженню фото-генерованих дірок до емітера, що призводить до збільшення швидкості рекомбінації електронно-діркових пар і, отже, до зниження енергетичної ефективності. З шириною забороненої зони 1,84 еВ гідрогенізований аморфний кремній a-Si:H є найбільш підходящим кандидатом для створення пасивуючого шару на поверхні кристалічного кремнію для цього типу сонячних елементів.

Ключові слова: Сонячні елементи, HIT, Аморфний кремній, Потенціальний бар'єр, SCAPS-1D, Характеристика *J-V*.