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Influence of interfacial oxide layer thickness on conversion efficiency of $SnO_2/SiO_2/Si(N)$ Solar Cells

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Abstract - *We have fabricated efficient and economical solar cells using tin oxide SnO_2 deposited onto silicon substrate by Atmospheric Pressure Chemical Vapour Deposition (APCVD) technique. This low-cost process is of the interest to deposit an interfacial oxide (insulator) layer SiO_2 with controlled thickness δ. It is observed that the presence of this interfacial layer considerably improves the open circuit voltage and the efficiency of the solar cell by reducing the dark current. In this paper, we studied the effects of interfacial oxide layer thickness δ on the efficiency and open circuit voltage of the $SnO_2/SiO_2/Si(N)$ solar cells. From our analysis, we have found that the efficiency of the cells increases at first with the interfacial oxide layer thickness δ, and after acquiring a maximum value falls with a further increase of δ. We have experimentally optimized the interfacial layer thickness for maximum efficiency. The effect of substrate doping profile is also investigated. Finally, the results for our best solar cells are presented and analysed.*

Résumé - *Nous avons fabriqué de manière efficace et économique des cellules solaires en utilisant l'oxyde d'étain SnO_2 déposé sur substrat de silicium par la technique du dépôt chimique en phase vapeur (APCVD) à la pression atmosphérique. Ce process à faible coût est l'intérêt de déposer un oxyde interfacial 'isolant', sur la couche de SiO_2 avec contrôle de l'épaisseur δ. Il a été observé que la présence de cette couche interfaciale améliore considérablement la tension en circuit ouvert et de l'efficacité de la cellule solaire en réduisant le courant d'obscurité. Dans cet article, nous avons étudié les effets de l'épaisseur de la couche d'oxyde interfaciale sur l'efficacité et la tension en circuit ouvert de la cellule solaire $SnO_2/SiO_2/Si$ (N). De notre analyse, nous avons constaté que l'efficacité des cellules augmente d'abord avec l'épaisseur δ de la couche d'oxyde interfaciale, et après acquisition d'une valeur maximale relevant au niveau e d'une nouvelle augmentation de δ. Nous avons optimisé expérimentalement l'épaisseur de la couche interfaciale pour une efficacité maximale. L'effet du profil de substrat de dopage est aussi étudié. Enfin, les résultats sur des cellules solaires sont présentés et analysés.*

Keywords: APCVD - Heterostructure - Tin oxide - Optimization - Efficiency - Solar cell - Photovoltaic conversion.

1. INTRODUCTION

There has been considerable interest in recent years directed toward the development of metal-insulator-semiconductor (MIS) solar cells. Very often in these structures, tin oxide (SnO_2), indium tin oxide (ITO), and zinc oxide (ZnO) were used in place of the metal electrode [1-5]. Among these, SnO_2 is chosen because of its high electrical conductivity [8, 10] and its transparency in the visible and infrared light [6-9], therefore it acts as a window for sunlight. Further, its refractive index lies in between 1.9 and 2.0

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and hence it can be used as an antireflection (AR) coating [9]. In addition, SnO_2 exhibits very good chemical resistance to the majority of chemicals used in the PV industry [1, 10].

Thus $SnO_2/SiO_2/Si(N)$ solar cell can be considered to be an heterostructure solar cell having wide band gap semiconductor (SnO_2) matched to a narrower band gap semiconductor (Si) with an interfacial oxide layer SiO_2. Basically, the SnO_2 film in this device is deposited by Atmospheric Pressure Chemical Vapour Deposition (APCVD). This APCVD process has the advantage that it can be used for depositing uniform, homogenous coatings on large surface areas at high deposition rates. The open circuit voltage of the solar cells is dependent on the interfacial oxide layer thickness which in turn is dependent on deposition parameters, such as the oxygen flow rate, deposition time and deposition temperature [1]. In our analysis, we have assumed a fixed value of surface state density D_S and only varied the interfacial oxide layer thickness δ δ which the influence on the device parameters of the realized cells is discussed. The exact role of this layer is clearly understood and presented.

Illuminating the MIS solar cell results in a voltage ' V ' across the cell, a part V_i appears across the interfacial layer of thickness δ , while the rest V_S appears across the depletion region of width ' W ' of the semiconductor. Thus:

$$V = V_i + V_s \tag{1}$$

The mechanism for the current conduction is tunnelling through the interfacial insulating layer [11].

2. EXPERIMENTAL PROCEDURES

Fig. 1 shows the structure of $SnO_2/SiO_2/Si(N)$ cell elaborated in our laboratory.

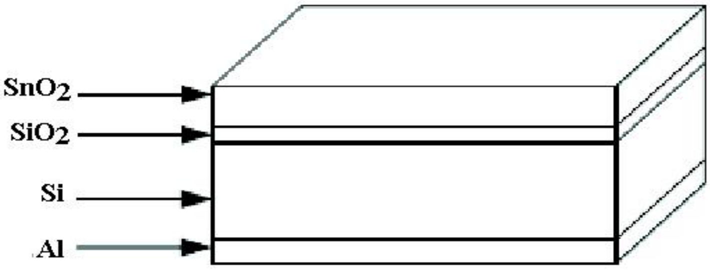

Fig. 1: Schematic diagram of the fabricated MIS solar cells

The photovoltaic cells were prepared by depositing the optimized tin oxide film on the monocrystalline N-type silicon substrate of (100) orientation and having a resistivity of 1-3 Ω.cm. After cleaning and etching the polished silicon surface, a layer of SnO_2 is deposited by APCVD technique described previously [1, 7]. The deposition temperature is between 350 and 500 °C. Tin dichloride is used as precursor for tin oxide deposition by applying the following oxidation reaction:

$$SnCl_2 + O_2 \rightarrow SnO_2 + Cl_2 \tag{2}$$

An Argon gas (Ar) was added in order to obtain a good uniformity of the film and to avoid undesirable oxidation. We realized the metal-insulator-semiconductor structure by depositing a fine oxide insulating layer between the silicon and tin oxide. For this, we sent an oxygen flow on the silicon substrate in the tube and this, before proceeding to the deposition reaction of tin oxide. The oxidation of silicon proceeds according to the following reaction:

$$\mathrm{Si} + \mathrm{O_2} \rightarrow \mathrm{SiO_2} \qquad (3)$$

This reaction principally depends on the temperature of the furnace, the oxygen flow rate and the duration of the reaction. The metallic contacts for solar cells are accomplished by serigraphy at high temperature.

3. RESULTS AND DISCUSSION

3.1 Influence of the interfacial oxide layer thickness on the open circuit voltage of the $SnO_2/SiO_2/Si(N)$ solar cell

From our experimental results, we noticed that the open circuit voltage of the heterostructure $SnO_2/SiO_2/Si(N)$ is better than that of the $SnO_2/Si(N)$ heterojunction. Fig. 2 shows the increase in V_{oc} with δ.

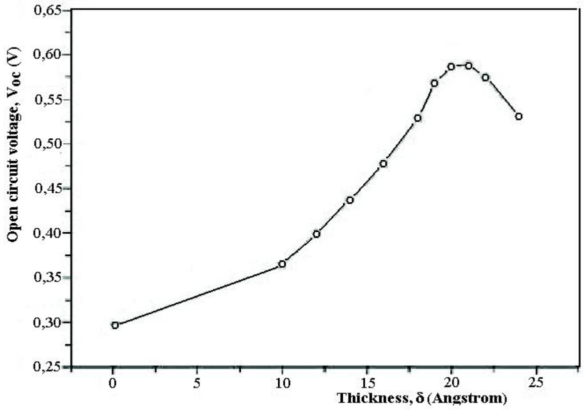

Fig. 2: The effect of the interfacial layer thickness δ on V_{oc}

The open circuit voltage is determined by the photo generated current I_{ph} and the reverse current I_0 as given in equation (4):

$$V_{oc} = \frac{k.T}{q} \times \mathrm{Ln}\left(\frac{I_{ph}}{I_0} + 1\right) \qquad (4)$$

where $q(C)$ is the electron charge, $k(J/K)$ is the Boltzmann's constant and $T(K)$ is the absolute temperature.

It can be shown that [2]

$$V_{oc} = n.\left[\Phi_{Bn} + \frac{kT}{q}.\chi^{1/2}.\delta + \frac{kT}{q}.\mathrm{Ln}\left(\frac{J_{sc}}{A^*.T^2}\right)\right] \qquad (5)$$

where $\Phi_{Bn}(eV)$ is the Schottky barrier height for N-type device, $\chi(eV)$ is the electron affinity of silicon, $\delta(A°)$ is the thickness of the interfacial oxide (SiO_2), $J_{sc}\left(A/cm^2\right)$ is the short circuit current for MIS cell, $A^*\left(A\,cm^{-2}\,K^{-2}\right)$ is the Richardson's constant, n is the diode constant.

The open circuit voltage initially increases with increasing the interfacial oxide layer thickness δ, but after a certain optimum, it decreases with a further increase of δ. This can be explained as follows. An increase in the interfacial oxide layer thickness δ, results in a decrease in transmission of electrons across the interfacial oxide layer and in the increased potential V_i appearing across the interfacial layer. This increase of V_i leads to an increase of the effective barrier height Φ^*_{Bn} which hinders the flow of majority carriers [11] as given in equations (6), (7). These two factors play a role in reducing the reverse current I_0.

$$\Phi^*_{Bn} = \Phi_{Bn} + V_i \tag{6}$$

$$\Phi_{Bn} = \gamma.\Phi_{B0} + (1-\gamma).(E_g - \Phi_0) \tag{7}$$

In which

$$\Phi_{B0} = \Phi_m - \chi \tag{8}$$

$$\gamma = (1+\alpha)^{-1} \tag{9}$$

$$\alpha = \frac{q.D_s.\delta}{\varepsilon_i} \tag{10}$$

In these equations, $\Phi^*_{Bn}(eV)$ is the effective barrier height, $\Phi_m(eV)$ is the metal work function, $D_s\left(cm^{-2}\,eV^{-1}\right)$ is the interface state density, $\varepsilon_i(F/cm)$ is the permittivity of the interfacial oxide layer (SiO_2), $\Phi_0(eV)$ is the level above valence band to which surface states are filled in isolated semiconductor, $E_g(eV)$ is the band gap of the semiconductor.

From equation (4), we see that a smaller I_0 gives a larger V_{oc}. Beyond a certain δ, the V_{oc} decreases due to a decrease in the photogenerated current for higher values of δ.

3.2 Influence of the deposition temperature

From our experimental study we noticed that at low deposition temperature, the open circuit voltage is low, but it increases with increasing deposition temperature and reaches a maximum at about 440 °C. But, after this optimum it decreases as a result of the presence of a too thick oxide layer (SiO_2) between SnO_2 and Si due to a fast oxidation of silicon at high temperature. This can be explained as follows. If the SiO_2 was thick, the transmission of electrons across the interfacial layer becomes small and in turn also reduces the transmission of the photo generated holes which would be forced to recombine with electrons in silicon leading to photocurrent reduction and thus to V_{oc} degradation according to equation (4).

3.3 Influence of the interfacial oxide layer thickness δ on the efficiency η of the $SnO_2/SiO_2/Si(N)$ solar cell

As can be seen in Fig. 3, the efficiency initially increases with δ because of the increase in photo generated current I_{ph}. A decrease in transmission of electrons with increasing the interfacial layer thickness δ, leads to reverse current I_0 reduction. Thus, the photo generated current increases. This explains the increase of efficiency with δ. After a maximum is reached, the efficiency decreases due to a decrease in the fill factor FF for higher values of δ according to equation (11).

$$\eta = \frac{J_{sc} \cdot V_{oc}}{P_i} . FF \tag{11}$$

where P_i is the incident power and FF is the fill factor.

3.4 Influence of silicon resistivity

For monocrystalline silicon $SnO_2/SiO_2/Si(N)$ solar cells, we have found that the open circuit voltage V_{oc} increases as the resistivity decreases. This can be explained as follows. For N-type silicon, a decrease in the resistivity results in an increase in the electron concentration. This causes a decrease in the hole concentration and thus a reduction in I_0, resulting in an increased V_{oc} according to equation (4). We deduced that, we were able to increase the open circuit voltage and thus the efficiency of the solar cells, when we decreased the resistivity of the silicon from 1 - 3 Ω cm to 1.2 - 2.5 Ω cm.

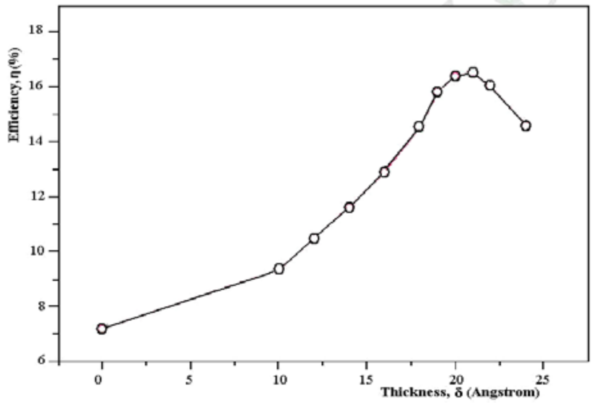

Fig. 3: The effect of the interfacial layer thickness δ on the efficiency η

4. CONCLUSION

The introduction of an interfacial oxide layer SiO_2 between SnO_2 and Si improves the performances of solar cell fabricated on N-type silicon. We have experimentally optimized the interfacial oxide layer thickness to about 21 A° for maximum efficiency as reported from simulation results [11]. From our experimental study, we have optimized the silicon resistivity to 1.2 - 2.5 Ω cm for maximum efficiency.

This shows that, $SnO_2/SiO_2/Si(N)$ solar cell has good potential and promise as an efficient, stable and economical solar energy converter.

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