Study and Fabrication of High Efficiency Indium Doped SnO_2/SiO2/ n– Si Solar Cells.

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Abstract

In this paper a new type of indium doped SnO_2/SiO_2/(textured) n-Si solar cell were prepared by vacuum evaporation source.. The SnO_2 layer is simultaneously an antireflection coating and a transparent upper contract. The interfacial layer plays an important role in determining the short circuit current, open circuit voltage, fill factor and efficiency of the cell. In this paper, the effects of interfacial oxide layer thickness, SnO2 layer thickness, indium layer thickness were studied. The indium doped SnO_2 layer reduces the cell series resistance and hence increase the cell output power, the performance parameters of the fabricated solar cell were as follows: an V_{oc} of 0.646 V, Isc of 29.6 mA cm^{-2}, a fill factor of 0.7 and a conversion efficiency of 13.38 at an AM 1.0 irradiance.

Keywords: SnO2, Solar Cells, High Efficiency.

دراسة وتصنيع خلية شمسية عالية الكفاءة نوع SnO2/SiO_2/textured(n-Si)

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ألخلاصة

تم في هذا البحث تحضير الخلية الشمسية نوع -SnO_2/SiO_2/textured(n-Si) باستخدام طريقة التبخير الفراغي. تعتبر مادة الـ SnO_2 كمادة مانعة للانعكاس وبنفس الوقت كطبقة نفاذة للضوء. تلعب مادة الاوكسيد العازلة SiO_2 دور مهم في تعزيز قيمة تيار الدائرة القصيرة , فولتية الدائرة المفتوحة ,عامل الملئ وكفاءة الخلية الشمسية .كذلك تم في هذا البحث دراسة تأثير كل من سمك طبقة SnO_2, SiO_2 ومادة الانديوم. تم قياس خواص الخلية الشمسية المصنعة وكانت: فولتية الدائرة المفتوحة مساوية لـ 0.646 فولت ، تيار الدائرة القصيرة بحدود 29.6mA ,عامل الملىء مساويا لـ 0.7 وكفاءة التحويل للخلية بحدود ٪13.38 عند ظروف إشعاع AM1.0.

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1.Introduction:

The wide band gap oxide semiconductor compounds such as In_2O_3, SnO_2 have the band gap more than 3ev and therefore are transparent to the radiation with the wave – length more than 0.4 µm, i.e for the wave – length from the region of the maximum solar intensity. Their conductivity could be changed within wide limits, from 10^{-1} ohm^{-1} cm^{-1} up to 10^4 ohm^{-1}cm^{-1}. The above-mentioned property permit to use this material in solar cell fabrication as front layer in SIS structures. The investigation of silicon based SIS structures began in 1979 [1]. It was showed that the most efficient solar cells obtained by spray deposition of ITO (Indium Tin Oxide) on the frontal layers of silicon [2]. The equilibrium band diagram for SnO_2/SiO_2/n-Si system is shown in figure (1).

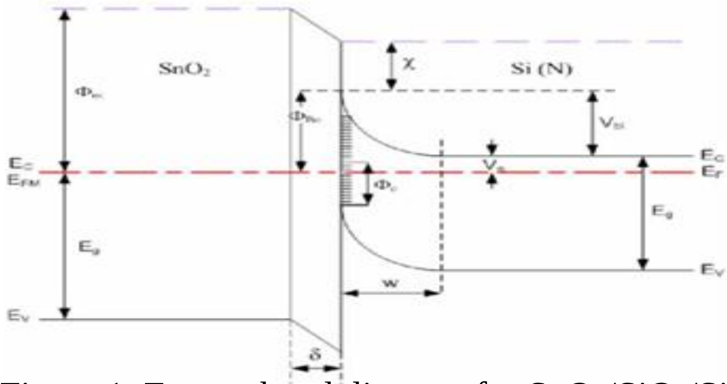

Figure 1. Energy band diagram for SnO_2/SiO_2/Si (n) solar cell under equilibrium conditions

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In MIS type devices, the interfacial oxide layer and the interface states can strongly affect the magnitude of barrier height. This is expressed as

$$\Phi_{Bn} = \gamma \Phi_{B0} + (1-\gamma)(E_g - \Phi_0) \quad \textbf{(1)}$$

$$\Phi_{B0} = \Phi_m - \aleph \quad \textbf{(2)}$$

$$\gamma = (1+\alpha)^{-1} \quad \textbf{(3)}$$

$$\propto = \frac{q}{\varepsilon_0}\left(\frac{D_s}{K_i}\right)\sigma \quad \textbf{(4)}$$

where Φ_m is the metal work function, E_g is the band gap of silicon, $\aleph$ is the electron affinity of silicon, δ is the thickness of the interfacial oxide layer (SiO_2), D_S is the interface state density, K_i is the relative dielectric constant of SiO_2 and Φ_{Bn} is the Schottky barrier height for n-type device.

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

$$V = V_i + V_s \quad \textbf{(5)}$$

The energy band diagram for SnO_2/SiO_2/Si (n) system under illumination is shown in figure (2).

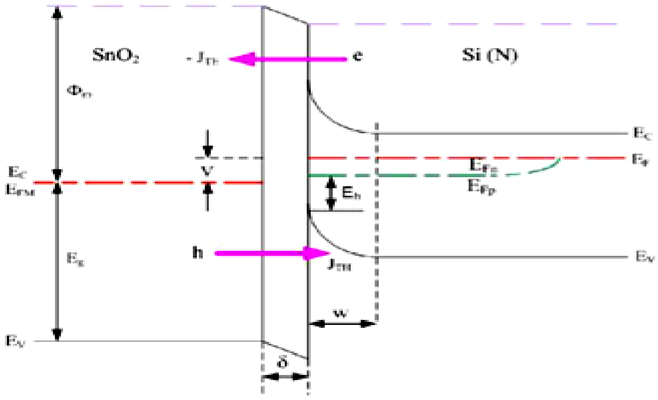

Figure 2. Energy band diagram for $SnO_2/SiO_2/Si$ (n) solar cell under illumination

The photo voltage (V) developed leads to a net current density (J) which is given by:

$$J = J_{TH} - J_{TE} \qquad \textbf{(6)}$$

J_{TH} is the hole tunneling current from the semiconductor to the metal, JTE represents the electrons tunneling current from the semiconductor to the metal. This is expressed as [18]:

$$J_{TE} = J_S\left[exp\left(\frac{qV_s}{KT}\right) - 1\right] \qquad \textbf{(7)}$$

$$J_S = A^{*}T^{2}\exp\left[\frac{-q.\varphi_{BN}}{KT}\right]\exp\left[-\chi^{1/2}\,\delta\right] \qquad \textbf{(8)}$$

In equation (8), X and δ are in units of eV and A° respectively. A* is the Richardson's constant, T is the temperature and K is the Boltzmann's constant.

The solar cell current-voltage characteristic developed under illumination is given by

$$J = J_{ph} - J_0\left[exp\left(\frac{q(\Delta)}{KT}\right) - 1\right] - J_S\left[exp\left(\frac{q.Vs}{KT}\right) - 1\right] \qquad \textbf{(9)}$$

$$J_o = \frac{P_{NO}\cdot q.Dp}{Lp} \qquad \textbf{(10)}$$

$$J_{ph} = q.\Phi\left[1 - \frac{exp(-\alpha' w)}{1 + \alpha' Lp}\right] \qquad \textbf{(11)}$$

$$\Delta = E_g - \Phi_{B0} - E_H \qquad \textbf{(12)}$$

In the above equations, J_{ph} is the photo generated current, J_S and J_0 are saturation and diffusion (holes) currents respectively, E_h is the minority carrier (hole) quasi-Fermi-level from the valence band at the surface ($E_h > 0.085$ eV for $N_D = 10^{18}$ cm^{-3}). P_{no} is the illuminated hole concentration far away from the junction, D_p is the diffusion coefficient for holes, L_p is the diffusion length, a' is the absorption coefficient of the material and Φ is the light flux density.

The spectral responsivity $S_{R(\lambda)}$ of a solar cell is defined as the short circuit current density per unit irradiance as a function of wavelength [4] . It is unit is ampere per watt and can be expressed as follow

$$S_{R(\lambda)} = EQE_{(\lambda)}/(hc/q\lambda) = [1 - R_t]\, IQE / (hc/q\lambda) \quad \textbf{(13)}$$

$$IQE(\lambda) = S_{R(\lambda)} .\, hC/q \,.\, L / (1 - R_t) \quad \textbf{(14)}$$

Where EQE is the external quantum efficiency, h is the Planck's constant, C is the speed of light, q is the electron charge, R_t is the structure total reflectance, and IQE is the internal quantum efficiency.

The SnO_2 has the quality of having high electrical conductivity and transparency at least in the visible region of solar spectrum. It's refractive index lies is between 1.9 and 2.0 [5] and hence can be used as a low resistance top contact to the junction and also as an anti-reflection coating for the active substrate.

2. The In-SnO_2 /SiO_2/n– $Si_{(n)}$ Structure Fabrication:

The fabrication samples were prepared by vacuum evaporation technique using Blazer unit (BA - 510) as a coating system . The textured n-Silicon wafers were subjected to a rigorous cleaning cycle in three steps, in order to reduce the pin holes formation [4]. Phosphorus doped n-type wafer (textured) with the thickness of 300 μm and resistivity of 1 Ω. Cm, orientated in (100) plane were used. A thin SiO_2 layer was deposited by vacuum evaporation technique on the cleared textured silicon surface. After the deposition of the SnO_2 layer with the required thickness on the SiO_2 layer, the wafer was placed inside an evacuated chamber in order to deposit the last indium layer, the samples then heated up to 150 °C for annealing purpose.

Aluminum thin film were deposited as back contacts for the fabricated samples. After the deposition of the aluminum film on the rough face of the wafer the fabricated samples were heated under vacuum to a temperature of 350°C for half an hour. This heat treatment is necessary to obtain an ohmic contact (back contact) between the aluminum and the wafers [5].

3. Results and Discussion:

3.1 The Electrical Properties of SnO_2 – Si(n) Structure.

The I-V characteristic of the SnO_2/SiO_2/(textured) n-Si structure for a SnO_2 thickness equal to 500nm and SiO2 thickness equal to 6nm is shown in Fig.(3) . The forward I-V characteristic for the SnO_2/SiO_2/(textured) n-Si structure were measured in the dark with annealing temperature range (25-150)°C. It is clear that the slope of the forward branches of the I-V characteristics does not depend on the temperature, such behavior of the forward current is characteristic for the case of tunnel processes

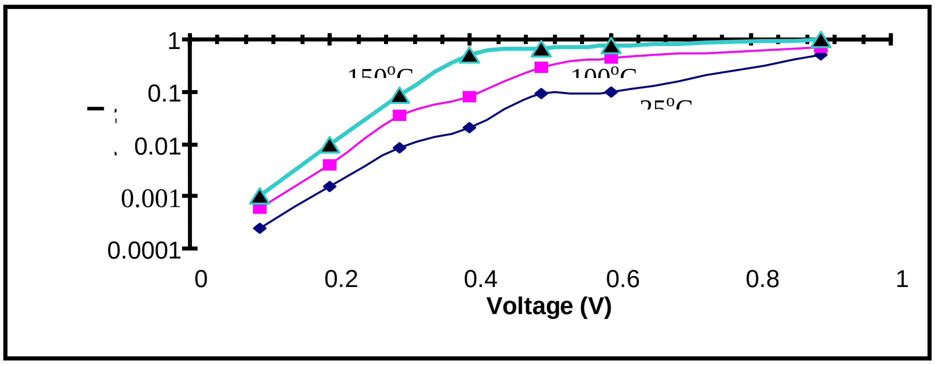

Fig .(3) . The forward I.V characteristic of the $SnO_2 – Si_{(n)}$ structures at different annealing temperature(SnO2=500nm,SiO2=6nm) .

The doping level of $Si_{(n)}$ (10^{15}) is too small for direct tunneling through the barrier, and the electron tunneling from the silicon conduction band in SnO_2 conduction band occurs at the participation of traps in the depletion region [6].

Figure (4) shows the reverse (I-V) characteristic of the SnO_2/SiO_2/(textured) n-Si structure at different annealing temperature.

The electron tunneling from the silicon conduction band into SnO_2 conduction band occurs at the participation of traps in the depletion region.

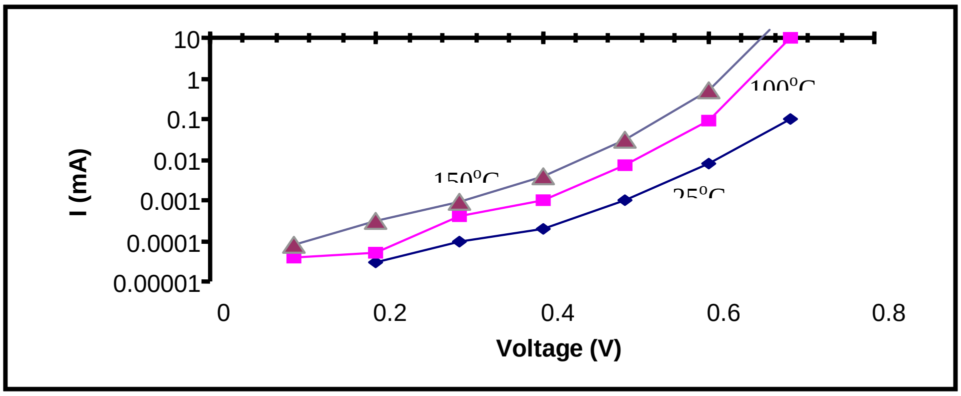

Fig . 4 . The reverse I.V characteristic of SnO_2/SiO_2/(textured) n-Si structures at different annealing temperature .

At voltage less than 0.65v the reverse current is nearly proportional to the voltage, but at voltage greater than 0.65v, a sharp rise of current due to tunnel transition of electron from the conduction band of SnO_2 into the conduction band of Si is noticed. The reverse current is determined by the transport of the minority carries from the Si valance band to the SnO_2 conduction band for the small bias up to 0.65 V. For large value of reverse voltage, the voltage drops to both the semiconductor and the insulation film. The almost linear depends of these characteristics demonstrate the power law depends of reverse current from voltage.

$$I_{rev.} = C.V^{n}_{rev}$$

Where C is a constant

This lead to the modification of the energetic band diagram and in this case the tunneling of the electrons from the SnO_2 condition band to the $Si_{(n)}$ condition band take place, which can be observed by the considerable rise of the reverse current as shown in the above figure.

3-2: The Photo – response of SnO_2/SiO_2/ n-Si Structure

The sensitive spectral response measurements technique is utilized to experimentally investigate the photo – response characteristic of SnO_2/SiO_2/(textured)n-Si structure. Such spectral response measurements enable the calculation of internal quantum efficiency (IQE), which is crucial to understanding and improving the production of solar cells .Fig. (5) shows the relative current response of the SnO_2/SiO_2/(textured) n-Si structure with different SnO_2 thickness, SiO_2 layer equal to 6nm and with 150^{o}C annealing temperature for an 30 minutes.

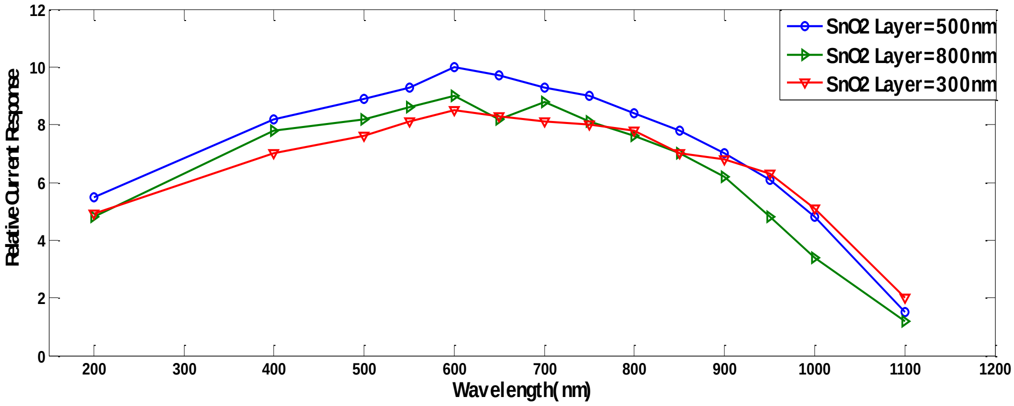

Fig. 5. The relative current response of the SnO_2 – 800nm $Si_{(n)}$ structure at different thickness (Ann Temp = 150^{o}C) .

It can be noticed that the maximum generated current is occurred with SnO_2 thickness equal to 500nm. Increasing thickness of SnO_2 layer will lead to lower generated current. The SnO_2 layer acts as a filter or a dead layer on the top surface, which prevents incident light from passing deeply into the sample.

The photoelectric properties have been investigated at the illumination of the structures through the wide gap semiconductor (SnO_2). The short circuit density depends on illumination intensity. The current starts increasing at λ > 200nm and the maximum current obtained at wavelength equal to 600nm. As λ increases above 1.0μm the relative current starts decreasing and still have a significant value of about 42%. The photosensitivity region of the SnO_2 – $Si_{(n)}$ structures is limited by the photon energies [6], which correspond to the band gaps of SnO_2 and Si. The generation and separation of electron – hole pairs occurs only in silicon while the entire space charge region is satiated here. Figure (6) shows the effect of indium doped layer at the top surface of SnO_2 layer of the SnO_2/SiO_2/(textured) n-Si structure

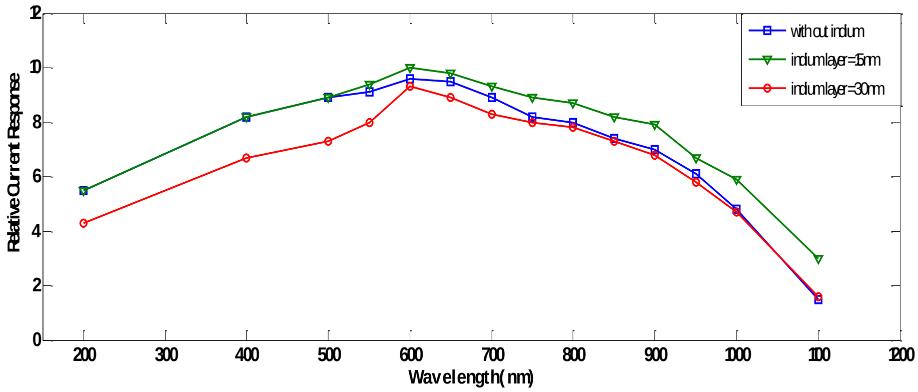

Fig. 6. The effect of indium doped layer on the response of SnO_2/SiO_2/(textured) n-Si structure .

It is clear that the photo current response of SnO_2/SiO_2/(textured) n-Si solar cell is increased at the beginning region of infrared wavelength using 15nm indium layer at the top surface of the cell and before annealing, increasing indium layer thickness tend to decrease the photo response of the solar cell . This is because large indium thickness will form a dead layer at the top surface of the cell and prevent light from penetrating inside the cell.

The effect of SiO_2 thickness on the SnO_2/SiO_2/(textured) n-Si open circuit voltage is shown in Fig. (7) .

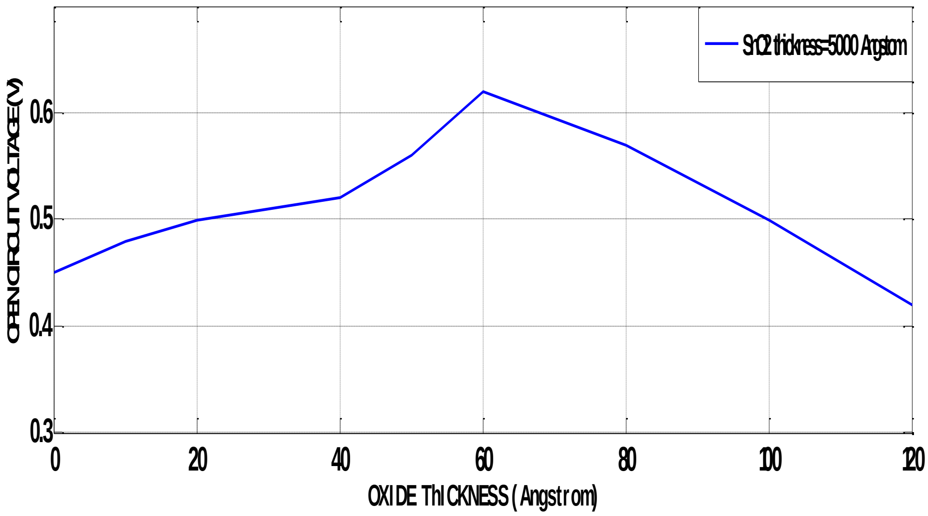

Fig. 7. The effect of SiO_2 thickness on the SnO_2/SiO_2/(textured) n-Si open circuit voltage

It is clear that the maximum value of the open circuit voltage (Voc) is occurred at oxide thickness equal to 6nm. The open circuit voltage increase with increasing the interfacial layer thickness SiO_2 in the initial stages is due to reverse current (JS) reduction and it can be said that increasing SiO_2 layer thickness will results in decreasing the transmission of electrons across the interfacial layer (SiO_2) and then the increasing of potential voltage Vi appearing across the interfacial layer. This increase in Vi leads to an increase of the effective barrier height Φ_{B0} which hinders the flow of majority carriers. These two factors play a role in reducing the reverse current J_S and hence the thermionic emission current J_{TE} [3].

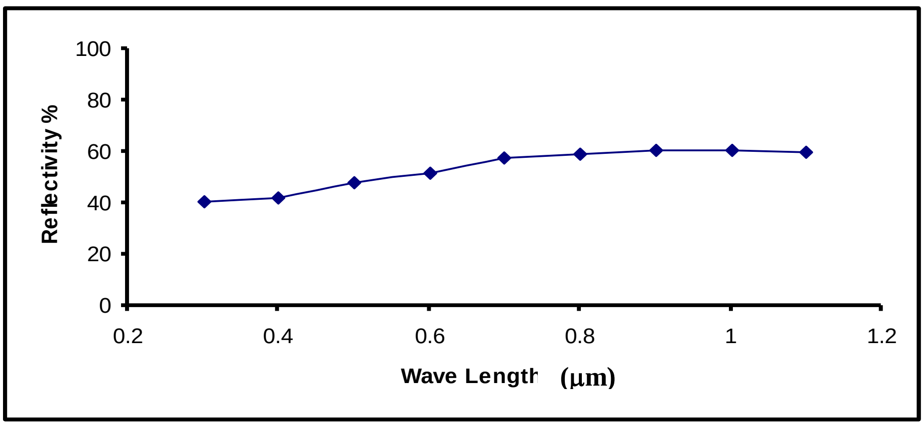

Fig.(8). Reflectivity versus incident light wavelength characteristic

The reflectance of the fabricated SnO_2/SiO_2/(textured) n-Si structure was measured using spectrophotometer. Figure (8) shows the relation between reflectivity and the incident light wavelength for a band between 0.3 to 1.1 micrometer .

The reflectance of the fabricated cell increases as the wavelength is moved toward the transmission region of silicon .It is has a value of 0.41 at short wavelength while this value increasing to about 0.61 at longer wavelength .The lower values of reflectivity can be attributed to the SnO_2 layer, which acts as an antireflection coating as well as a transparent upper contact.

The relative internal quantum efficiency (IQE) of the fabricated cell is calculated according to equation (14). Figure (9) shows the relative IQE for the fabricated SnO_2/SiO_2/(textured) n-Si structure with 500nm thickness and 150^{o}C annealing temperature .

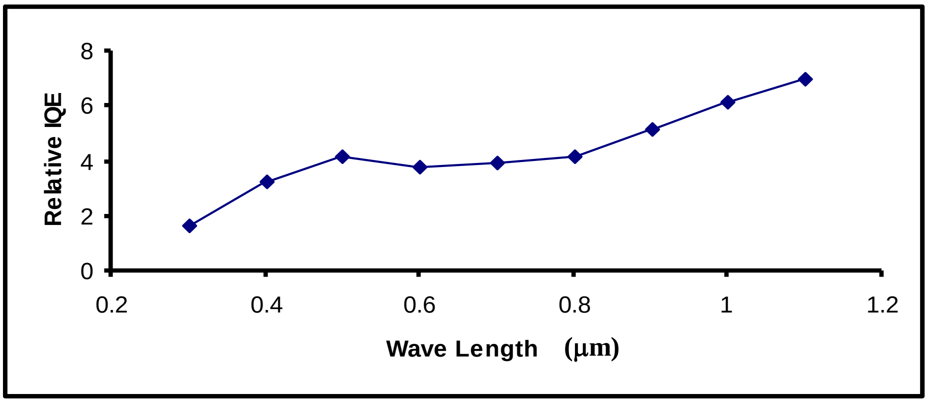

Fig.(9). Relative IQE verses incident light wavelength for the fabricated SnO_2- $Si_{(n)}$ structure (SnO_2 = 500nm , SiO2=6nm,T = 150 ^{o}C).

The IQE is a more fundamental quantity, which differs from EQE in the term (1- R_t), which accounts for reflection losses. It is clear that the IQE of the fabricated cell increases with the increasing of wavelength. The cell exhibit about 40 % IQE at wavelength of up to 750 nm . The IQE start to increase at wavelength equal to 900 nm , and the maximum IQE value occurs at wavelength equal to 1050 nm .In practice, IQE cannot increased more at long wavelength because of parasitic absorption losses, such as absorption in the rear reflector and free carrier absorption [9] .

The current – voltage characteristic for the In- SnO_2/SiO_2/(textured) n-Si solar cell at AM 1.0 condition is shown in figure (10).

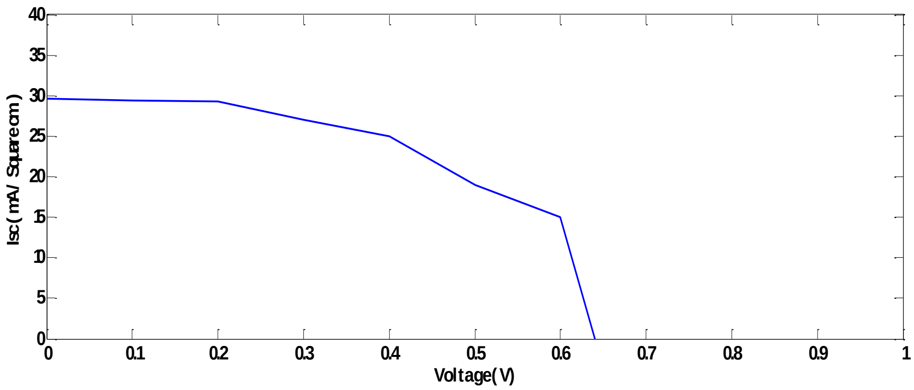

Fig. 10. The I.V load characteristic of the In- SnO_2/SiO_2/(textured) n-Si solar cell.

The incident power was at Am 1.0 irradiance and the SnO_2 – $Si_{(n)}$ structure is fabricated with SnO_2 thickness equal to 500nm doped with 15nm indium layer, the SiO_2 layer thickness is 6nm and the annealing temperature is 150°C for an 15 minutes. The photoelectric parameters determined from these characteristics are the open circuit voltage is equal to 0.646V, the short circuit current I_{SC} = 29.6mA/cm_2,the fill factor = 0.7 and the efficiency of the In- SnO_2/SiO_2/(textured) n-Si solar cell was about 13.385%.

4. Conclusion:

The In- SnO_2/SiO_2/(textured) n-Si solar cell was fabricated using vacuum evaporation technique, the In- SnO_2 layer acts as antireflection coating and a transparent upper contact. The oxidation of the silicon surface takes place simultaneously by heat treatment during the evaporation process.

The photoelectric characteristics of the fabricated solar cell was studied and measured it is found that the I-V curves for small direct bias correspond to the tunneling mechanism of charge carries transport through the interface. The effect of layers thickness of SnO2, SiO2 and In were studied and measured to find the optimum values that gives maximum solar cell efficiency.

The fabricated solar cell has a maximum response at wavelength between400-900 nm, the short circuit current was 29.6mA/cm^2, the open circuit voltage was 0.646V, the fill factor was 0.7 and the solar cell efficiency was equal to 13.385%.

5. References:

1. Shewchun J., Dubow J., Wilmson C. W, Wager J. F. (1979). The operation of semiconductor – insulator – semiconductor solar cells. Experiments. J. Appl. Phys., 50, 2832-2839.
2. Plattner R., Stetter W. and Kohler P. (1988). Transparent Conductor Tin – Oxide Layers for Thin – Film Solar Cells . Siemens Forsch - Entwick – Ber Bd. 138-146.
3. Bobeico Euqenia. Spray – Deposited SnO_2 – Si Solar cell. ISES solar world congress 1999, Volume 1.
4. Fahren bruch A. L. and Bube R. H. (1983). Fundamentals of Solar Cells, PP. 417-463. Academic Press, New York.
5. William, D. and J. R. Callister (1985). Material Science and Engineering. Ed. Wiley, J., Inc., New York.
6. Riben A. R. and Feucht D. L. (1966). Electrical transport in nGe – PgaHs heterojunction. Int. J. Elector.
7. M. A. Green, “Silicon Solar Cells: Advanced Principles and Practice”, Centre for Photovoltaic Device and systems. Sydney, (1995).
8. C.B. Honsberg ,F . Yon, M.A. Green, and S .R. Wenham, “Mechanically grooved ,Multi-Junction, Integrated Rear Contact Silicon Solar Cells For Low lifetime Substrate” . European Photovoltaic Solar Energy Conference .(1994)
9. D.Hocine, M S Belkaid, " Influence of interfacial oxide layer thickness on conversion efficiency of SnO2/SiO2/Si(N) Solar Cells" Revue des Renouvelables VOL. 11 No 3 (2008).
10. M. Batzill and U. Diebold, ‘The Surface and Materials Science of Tin Oxide’, Progress in Surface Science, Vol. 79, pp.4 – 154, (2005).

The work was carried out at the college of Engineering. University of Mosul