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## Enhance the solar cell efficiency by reduction of reflection losses

**Rawa K. Ibrahim\*, Mohanad M. Azzawi\*, Osama N. Naji\*\*, Naseer M. Hadi\***

**\*Directorate of Materials Research, Ministry of Science and Technology,  
Baghdad , Iraq**

**\*\*Department of Physics, Collage of science , University of Baghdad ,Baghdad,  
Iraq**

**[Rawak2070@gmail.com](mailto:Rawak2070@gmail.com) , [mohanad\\_1965@yahoo.com](mailto:mohanad_1965@yahoo.com)**

### **Abstract**

The enhancement of the solar cell efficiency field has been achieved in many methods due to the different factors and conditions that led to loss the solar energy .This work deals with the increasing of the efficiency of solar cell that made of single crystalline silicon .This increment achieved by the reduction of biggest type of losses of the conversion efficiency named reflection . by using two methods first ; forming grooves on the surface using pulse Nd:YAG laser with max energy 1J and pulse width 10ns, using the fast and accurate movement of the 3D optical galvo mirror scanning system to form the grooves , the second method was by deposition nanomaterials as Silver (Ag) and Cadmium telluride (CdTe) to constitute an antireflection layer for the incident solar spectrum . The effect of antireflection layer material type and the effect of incident light angle on the reflection had been studied in this work .The reflectance had been measured by a system designed and built to give the reflection for angles ranged 0 – 180 degree controlled by Microcontroller. The result indicate that increase in conversion efficiency was 28.3% for Ag/Si , and 32.9% for CdTe/Si than the original efficiency of Si solar cell.

**Keywords** : laser texture , silicon solar cell, antireflection surfaces , nanoparticles ,reflectance .

### **Introduction**

Most fundamental concepts to understanding solar cell operation is that the amount of electricity generated depends on the amount of light available for conversion. The increasing of amount of light absorbed by the cell is a subject of research and development common to all solar technologies and to all levels[1].

In this work, the common solar cell which made of Si wafer have been tested. The two benefit of majors light – trapping features ; first is the antireflecting layer deposited on the surface , second is the texturing of the silicon front surface ,which causes the incoming light to scatter at a shallow angle when it inter the silicon, which increasing the traveling path through the wafer and increase the photon absorption, also the texturing will make the light reflects in angle allows a second reflection transmitted the wafer[2] , all these can be shown in fig (1).



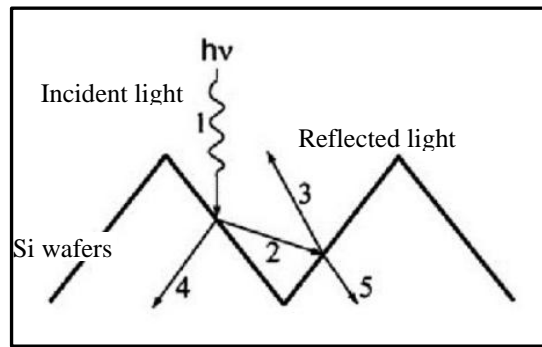


Fig (1) The reflection behavior of the text surface, (1) Incident light, (2 and 3)reflected light ,and (4 and 5) absorbed light [2].

### Theoretical Part

The reflectance of the surface properties can be represented by Bidirectional Reflectance Distribution Function (BRDF) [3], Which it is expression of the physical property of a material and describes the pattern of light reflected from the metal surface to all directions above the surface. The geometry of BRDF is shown in fig (2).

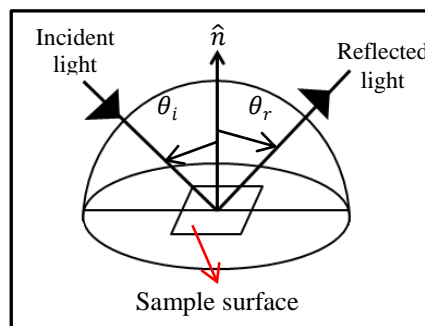


Fig (2) The geometry of the surface reflectance ,  $\hat{n}$  is the normal,  $\theta_i$  is incident angle ,  $\theta_r$  is reflected angle [3] .

The bidirectional reflectance distribution function (BRDF) is defined as the ratio of the directional reflected radiance to the directional incident irradiance. The BRDF was first defined by Fred Nicodemus around 1965 [4]The definition is:

$$f_r(w_i, w_r) = \frac{dL_r(w_r)}{dE_i(w_i)} = \frac{dL_r(w_r)}{L_i(w_i) \cos \theta_i dw_i} \quad \text{--- (1)}$$

where  $L$  is radiance, or power per unit solid-angle-in-the-direction-of-a-ray per unit projected-area-perpendicular-to-the-ray,  $E$  is irradiance, or power per unit surface area, and  $\theta_i$  is the angle between  $w_i$  and the surface normal . The index  $i$  indicates incident light, whereas the index  $r$  indicates reflected light. Radiance is the radiant power flow per

unit solid angle and unit area normal to the rays and has the unit  $[Wm^{-2}sr^{-1}]$ . Spectral radiance is the radiance per unit wavelength and has the unit  $[Wm^{-3}sr^{-1}]$ . Irradiance is the power flux density irradiating a surface per unit area of the surface and has unit  $[Wm^{-2}]$ . Spectral irradiance is the incident irradiance expressed in per-unit wavelength with unit  $[Wm^{-3}]$ . If the incident and reflected directions are reversed, the function has the same value. Further, the radiance does not vary along the

direction of propagation of a ray, in the absence of out-scattering or in-scattering along the ray. This will allows to measure the reflected radiance at any distance from the reflecting surface . BRDF is difficult to measure, because it is a function with four degrees of freedom , requires large data storage ( because for each incident direction the intensity of reflectance in all directions should be measured and stored). Because the BRDF is a function of four angles, such a device must have at least four degrees of mechanical freedom to measure the complete function.

So a design for measured the best angle of incident light hits the texture surface ,that makes the reflection loss minimum being very important. The present design in this work includes a fix light source , a material sample that can be rotated in angles range 0- 180 degree , and a photometer stand on fixed table . Moreover in this design the only free element to move was the angle of incident light . The rotation movement of sample achieved using stepper motor drives by microcontroller ,that programmed to get accurate rotation angle controlled by a cell phone via Bluetooth media.

The previous geometry of reflection measurement may put here as a historical review, the first on was Murray-Coleman's directional reflectometer [5] , designed by Murry-Coleman and Smith is shown in fig (3) .

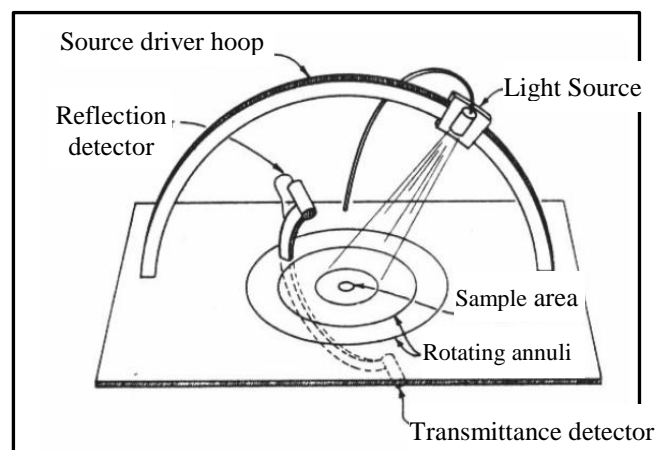


Fig (3) Gonio reflectometer designed by Murray-Coleman and Smith [5]

In this system, the source, the detector and the sample are all positioned with stepper motors that are controlled by a computer via standard RS232 serial port. The system provides four degrees of freedom, as required by the definition of the BRDF.

The other system is Ward's silver hemisphere reflectometer [6] in Lawrence Berkeley Laboratory, the development of the system by a relatively simple device for measuring BRDFs using imaging technology. The basic arrangement of the imaging Gonio Reflectometer is shown in Figure (4). Furthermore the key optical elements are a half-silvered hemisphere and a CCD camera with a fish-eye lens were used. Has two degrees of freedom handled by a mechanically controlled photometer in Murray's gonio reflectometer.

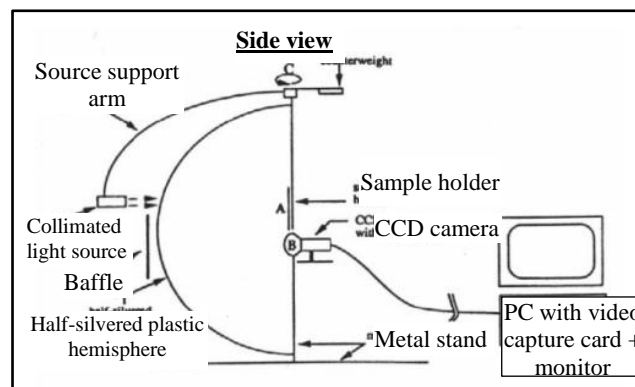


Fig (4) Ward's silver hemisphere reflectometer [6]

Reflectivity can be defined as a property of the material itself, most surfaces can be divided into those that give specular reflection (specular reflection is the mirror like reflection of waves) and diffuse reflection (diffuse reflection is the reflection of light or other waves or particles from a surface such that a ray incident on the surface is scattered at many angles rather than at just one angle as in the case of specular reflection). For specular surfaces, such as glass or polished metal, reflectance will be nearly zero at all angles except at the appropriate reflected angle. The reflected radiation will follow a different path from incident radiation for all cases other than radiation normal to the surface. For diffuse surfaces, such as matte white paint, the reflectance is uniform to all angles equally or near-equally. Such these surfaces are said to be Lambertian. (Lambertian reflectance is the property that defines an ideal "matte" or diffusely reflecting surface).

The apparent brightness of a Lambertian surface to an observer is the same regardless of the observer's angle of view. Most real objects have some mixture of diffuse and specular reflective properties.

The reflectance can be reduced by depositing a layer of different material that called antireflection layer , moreover by changing the surface morphology utilizing different methods such as chemical etching ( using strong acids like HF , HNO<sub>3</sub> , or strong alkane like NaOH, KOH ) , mechanical scribing , surface grooving , surface engraving ,and laser surface texturing .

The refractive index of deposited layer is highly affecting the reflectivity property of the layer . The two materials were used in this research are Ag and CdTe ,and the refractive index was 1.2 and 2.7 respectively. (The refractive index at the nanoparticles case will be larger).

The reflectivity also will be effected by the surface morphology due to double photon absorption ( The reflected photon will absorbed again depending on the incident angle) because the surface textured by laser ,in this research pulsed Nd:YAG laser with max energy 1J and 10ns pulse width has been used.

The reflectance can be also calculated from Fresnel equation:

$$R = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2 \quad \text{-----}(2)$$

Where R : reflectance

$n_1$  and  $n_2$  : refractive index of first media and second media respectively.

From this relation the reflected and transmitted light can be determined. (the transmitted light calculate as :  $T = 1 - R$  ,where T : transmittance ). Fresnel's formulae give the proportions of light that are reflected and transmitted by an interface between media with distinct refractive indices. They depend on the orientation of light and on the refractive indices of the two media [7].

The reflectance also depend on the optical energy gap of the semiconductor materials . The large energy gap mean low absorbance and high reflectance [8].

The silver nanoparticles used in this research as antireflection deposition layer it's lumo - homo gap 2.242 eV and the other type of antireflection layer used CdTe nanorods with energy gap 1.807 [9] .

The reflectance in this work was calculated from the square of the reflectivity [7]

$$P(\lambda) = \frac{G_r(\lambda)}{G_i(\lambda)} \quad \text{-----}(3)$$

where  $P$  is the reflectivity

$\lambda$  is the wavelength of the light which is the He-Ne laser(632.8nm)

$G_r$  is the reflected radiation

$G_i$  is the incident radiation.

The solar efficiency was calculated from

$$\eta = (I_{sc} \times V_{oc} \times FF) / (G \times Area) \quad \text{-----(4)}$$

where  $G$  is the power of the lamp ( 250 W)

$Area$  of the solar cell ( $1 \text{ cm}^2$ )

or from

$$\eta = \frac{P_{out}}{P_{in}} \quad \text{-----(5)}$$

Where  $P_{out}$  the output power at max point

$P_{in}$  the input power .

### **Experimental work:**

The first nanomaterials used as antireflection layer was silver nanoparticles with particle size (5-11)nm and absorption peak at 480nm as shown in fig (5) ,while the second was CdTe nanorods with particle size 10nm and absorption peak ranged (340 -460) nm (which they prepared previously by our laboratory )as shown in fig (6)[9].

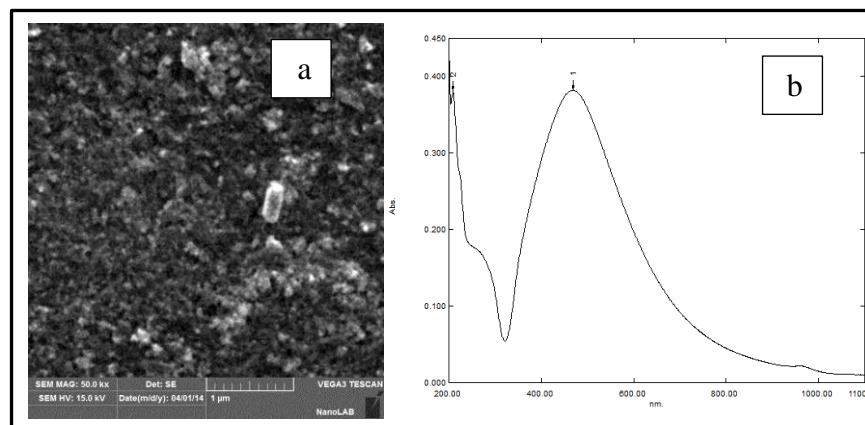
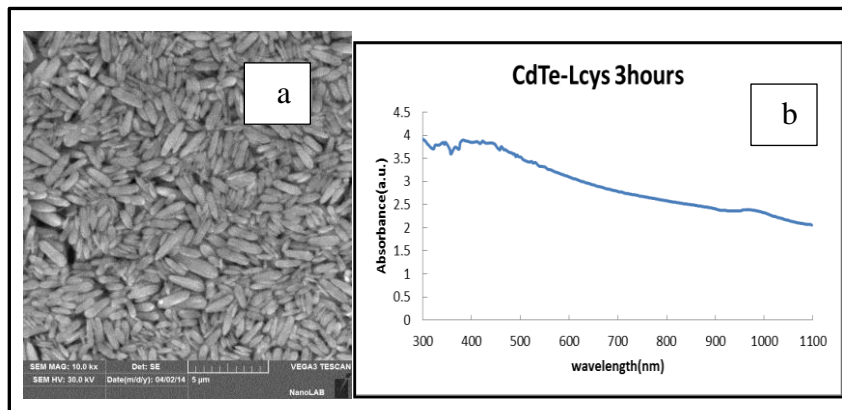


Fig (5) a- the SEM of the Ag NPs , b-the Absorption Spectrum of The Prepared Ag NPs.



Fig(6) a- the SEM of the CdTe nanorods, b- the absorption spectrum of the CdTe nanorods.

The reflection of light system have been designed and built as can be shown in fig (7), the designed system consists of stepper motor with rotation degree ranged  $0^{\circ}$ - $180^{\circ}$  controlled by Unio microcontroller from Ardiuno. The phone cell was used to control the movement of the stepper motor via Bluetooth media. In addition photoresistor LDR array were used to detect the change in the light reached the solar cell as voltage which displayed in LED screen.

To simulate the solar spectrum Halogen lamp of power 150W had been used to illuminate system to measure the solar cell efficiency and the current –voltage (IV) characteristic. This system consisted of solar cell holder, power supply, digital multimeter, variable resistor ( $1K\Omega$ ), as shown in fig (8). a fabricated solar cell of Si, Ag/Si, and CdTe/Si of  $1\text{ cm}^2$  were used for the measurements.

The reflectance can be calculated by comparing the amount of reflected radiation to the amount of incident radiation.

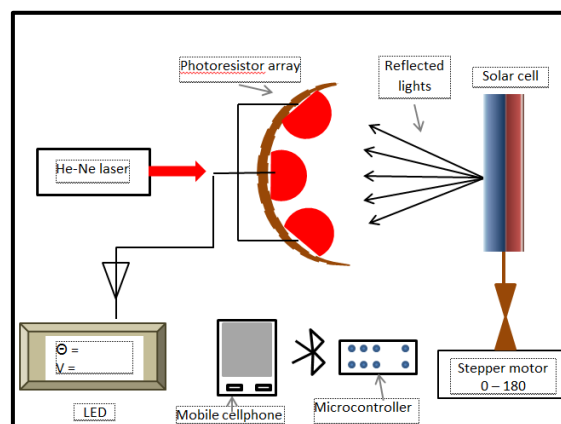


Fig.(7) The reflection system measurement of solar cell.



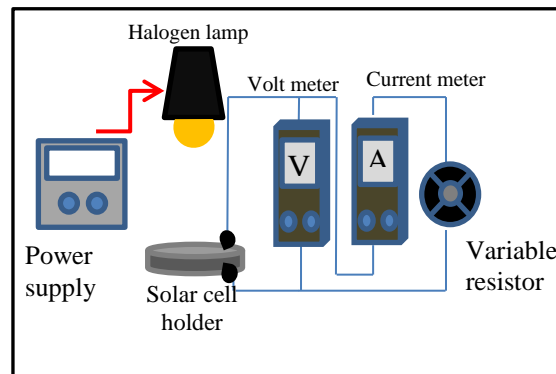


Fig. (8) The experimental setup for IV Characteristic measurement of solar cell.

### **Results and Discussion :**

The relation of incident light angle and the output voltage from photodiode can be shown in fig (9) for the three samples ( Si , Ag/Si ,and CdTe/Si ), hence that the lower output voltage will be read from the photo detector represents lower light reflection .

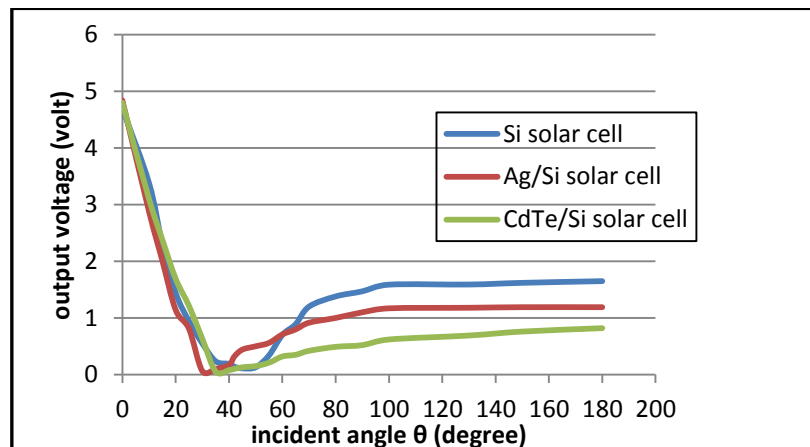


Fig (9) The relation of incident angle (0-180 degree) of laser exposed the solar cell and the output voltage.

Table 1 illustrate the reflectivity of the three solar cell samples and the best incident angle of the light.

Table 1 Reflectivity of the different solar cell and the incident angles

Sample	Best incident angle $\theta$ (degree)	Reflectivity R ( %)
Bare Si solar cell	45	91.957
Nanosilver/Si solar cell /laser processed	31	9.182
Nanosilver/Si solar cell/without laser processed	42	9.361
Nanorod CdTe/Si solar cell/laser processed	36	15.75
Nanorodn CdTe/Si solar cell/without laser processed	38	15.82

So when the refractive index of the material is decrease the energy gap is increase but absorb . and the reflectivity is decrease[Indolia ,2017] (lumo - homo gap for Ag NPs was 2.242 eV and for CdTe nanorods was 1.807eV[Ibrahim, 2015], because the matter absorbed more light and release more free electrons that participated in the generated electric current. For this reason , the Ag/Si solar cell have the lowest reflectivity than the CdTe/Si solar cell.

Fig (10) shows the  $I$ - $V$  curves obtained for each of the solar cell samples , using the setup in fig (6 ) ,( reference sample ,nanosilver and nanorode CdTe ) ,while table 2 illustrate the results obtained from the  $I$ - $V$  curves. Where  $I_{sc}$  is the short-circuit current at zero voltage and  $V_{oc}$  is the open-circuit voltage at zero current.

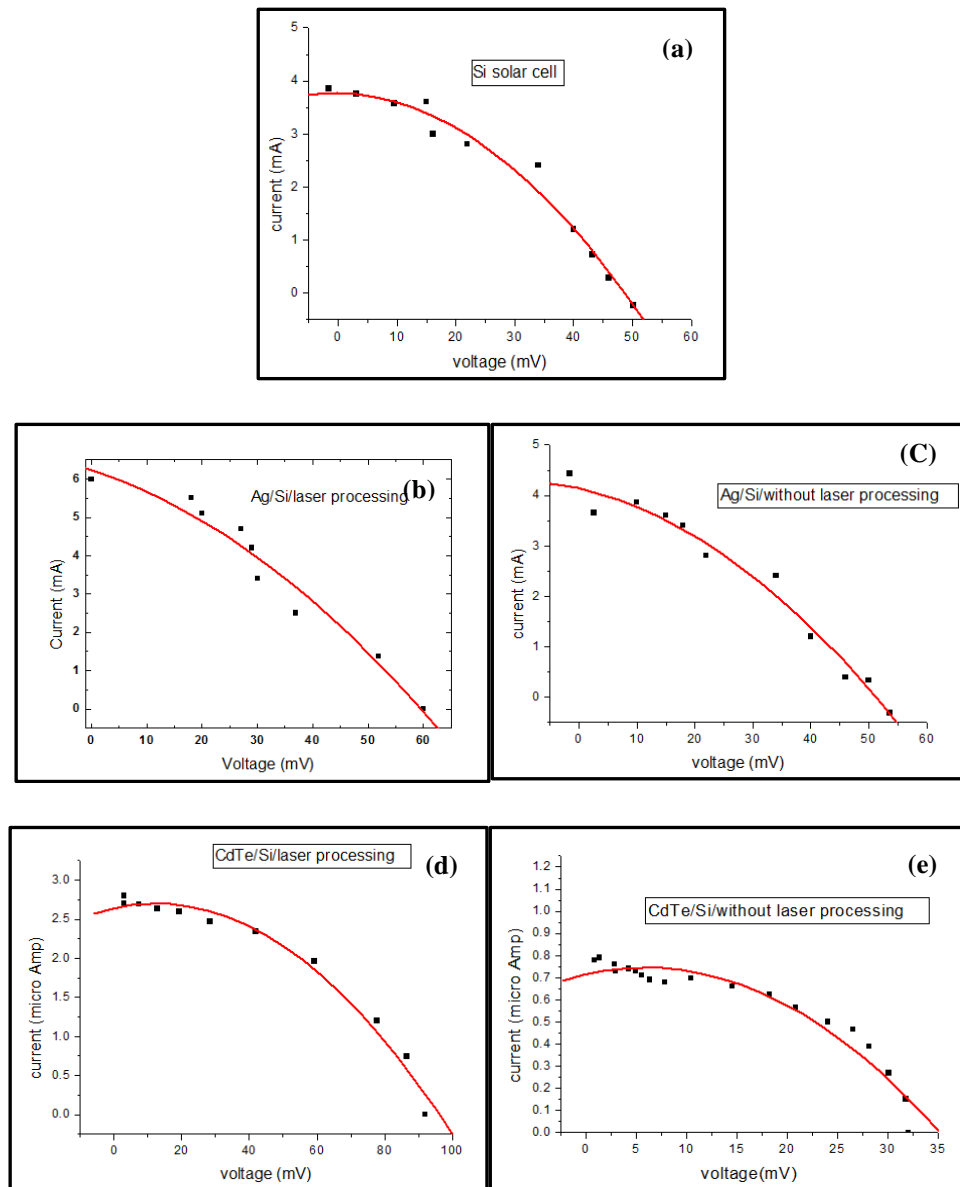


Fig (10) The IV curve of (a ) Si Solar cell ( b ) Ag/Si /laser processing, ( c ) Ag/Si/without laser processing, (d) CdTe/Si/laser processing, (e) CdTe/Si/without laser processing.

Table 2 The efficiency of different solar cell

Sample	$I_{sc}$	$V_{oc}$ mv	$P_{in}$ (mW)	$P_{out}$ (mW)	$\eta$ (%) efficiency
Bare Si solar cell (without laser processing)	4.4mA	55	2.45	0.47775	19.5
NPs Ag/Si / Laser processing solar cell	6.4mA	78	2.45	0.66618	27.2
NPs Ag/Si/ without laser processing solar cell	0.8mA	68	2.45	0.54635	22.3
Nanorod CdTe/Si / Laser processing solar cell	2.7 $\mu$ A	92	2.45	0.71968	29.1
Nanorod CdTe/Si/without laser processing solar cell	0.77 $\mu$ A	34	2.45	0.62965	25.7

The presented results of angle-dependent reflectance measurements on photovoltaic materials shown that the reflectance of laser processed silicon solar cell, laser processed / Silver/Silicon solar cells , and laser processed CdTe/Silicon solar cell samples are very depending on the incidence angle of the light. The results evidence the superior light trapping performance of photons by the laser texture surface and the deposition layers of the CdTe and Ag on the Si wafer.

The reflectance and the efficiency of the Ag /Si sample compare with CdTe /Si sample at different incident angles to put the best angle of light incident exposed the solar cell at outdoor field.

The best incident angle was ranged 31- 45 degree due to reduce the random scattering and reflection to achieve enhance absorbance of solar cell . ,while the best nanomaterial deposition layers from the reflectance and efficiency measerments , was for the CdTe nanorods due to its low energy gap (1.88eV) than The Lumo-Homo energy of Ag nanoparticles (2.44eV).

### **Conclusions**

The effect of light incident angle on the efficiency of solar cell have studied by reducing the reflection loss .The results support that the best solar cell efficiency increased by 28.3% percentage for the Ag/Si solar cell , and 32.9% percentage for CdTe/Si solar cell respect with the reference Si solar cell .

The incident angle of the light to reduce reflection loss was 38 ° for CdTe/Si/ without laser processing , 36 ° for CdTe/Si/ laser processing, 42 ° for Ag/Si/without laser processing , 31 ° for Ag/Si laser processing ,and 45 ° for Si solar cell . The results showed that the absorbance increase due to increase the light entrapment by the texture surface and the deposition nanomaterial (CdTe,silver nanoparticles ) layer.The best result gets was the CdTe/Si solar cell because the minimum reflection loss and high conversion efficiency .

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