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The Effect of Different Surface Plasmon Polaritons Shapes on Thin Film Solar Cell Efficiency

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Abstract – Thin film Si solar cell and surface plasmon polaritons (SPPs) effects on solar cell efficiency, series resistance and shunt resistance are studied and analyzed in this work. The different surface plasmon polaritons (SPPs) shapes and their effects on the optical, electrical properties and therefore on the efficiency of thin film solar cell are studied in this work. This study is introduced using 3D numerical simulation results. The semiconductor and electromagnetic models are incorporated for studying the electrical and optical behaviors of the thin film solar cells, respectively. A 14.76% efficiency is obtained for triangle' SPPs of about 1.07% of efficiency improvement compared to solar cell of SPPs free. The solar cell electrical parameters also are extracted in this work based on a single diode equivalent model. The series resistance is enhanced for solar cells of equilateral triangle SPP by 3% compared to the non-applied SPPs.

1.INTRODUCTION

Photovoltaic is the cleanest way to get an electric energy by converting the solar energy into electrical energy [1].

The demands for increasing the photovoltaic efficiency is the main challenge that facing the solar cell usages spreading and mass production respecting the cost. This due to the material and process expenses, definitely for bulk silicon based solar cells [2].

The thin film solar cells have reduced the cost by replacing the bulk substrate by thin film layers instead of the bulk one. The main issue of using the thin film technology is reducing the absorbed energy level down to the semiconductor material energy gap. Thin-film silicon solar cells have different advantages but they still want to achieve moral efficiency and improve production methods. Thin-film silicon solar cells technology has clashed with recent crystalline silicon cells, utilizing a limited amount of active materials and record low-thermal growth. Although crystalline silicone solar cells grow rapidly in thin-film [3-6].

Plasmonics paid great attention to these challenges by using metals to harness light during a deep-subwavelength calculation; plasmonics have accepted a substantial

reduction in photonic system size [7-10]. Plasmonic gratings-periodic metallic structures on surfaces used to enhance plasmonic fields. The grating increases plasmonic pattern propagation along the grating. Beyond the waveguide attitude, an apparent advantage of this mode of plasmonic improvement is that it does not require unconnected couplings. The optical fiber geometry can accompany these geometries for the detector. Overall, plasmonic grating-type detectors are better suited to obtain the signal directly from free space than the wave-guide-form due to wave-guide coupling failures [11-13].

Surface plasmon polaritons (SPPs), elevating excitations along metal-dielectric boundaries arising from the combination of light and cooperative fluctuations of uncontrolled electrons, have attracted considerable attention in the research regions of physics, chemistry, biology and material science, especially (lower diffraction threshold) due to their exclusive properties [14-17].

The manufacturing techniques and applications of SPPs in solar cells are growing rapidly in recent years. A new crystalline silicon solar cell, with Si nano-cone arrays on the top and Al nano-hemisphere arrays on the bottom side. The 3D numerical simulations using COMSOL Multiphysics systematically studied the capacity to trap light. The nano-cone arrays gain light fastening by adding gradient refractive shift incident light is indexed and integrated into optical modes. The metallic nano-hemisphere arrays affect light harvesting by polaritons of surface plasmon (SPPs) and the scattering effect [18]. A new standard α -Si thin solar cell film. We build Ag nanograting to spread more light incident. It also exhibits in the meantime a silver/S- α plasmonic interface enhancement. Energy caught The design will increase short circuit current density to 23.74 mA/cm² on both front anti-reflective coating and the back metal reflector. From 300 nm to 950 nm, over the solar spectrum. This style we also find can maintain a high density of the short circuit current within a wide incidence angle variation [19]. COMSOL Multiphysics, a package for finite elemental analysis, is used to research the effect of nanograting structures on a-Si thin film solar cell. The method gives the requisite geometry simulation economic efficiency and convenience. Nevertheless, it can be said that various tests were conducted before actual calculations were carried out to authenticate the proper functioning of the model using Fresnel equations well known in literature. The effects on light trapping (absorption) are regulated by seven gate structures with variable slit widths (slits). The construction of the grating becomes simpler to produce Optical antennas and separated ring similar to nanoparticles Resonators and so forth [20]. Silver nanoparticles combined with a thin-film solar cell (TFSC) silicon. It is made of TiO₂ pyramids in which the antireflective layer is made of anti-reflective layers. The goal of this structure is to allow sunlight to penetrate the cell at any angle with the minimum reflexion. and 300–1100 nm wavelength absorption. Silizium is the absorbing layer, and the molecular bonds break down and discharge many electrons by their high absorption rate when sunlight enters this layer. Silver spherical nanoparticles are positioned in this layer to increase solar energy absorption through localized plasmon resonances on the surface [21]. Plasmonic grating on the surface is very useful for controlling the absorbed light, manipulating and detecting light with specific polarisation. The plasmonic grating contributes to increased absorption and shows excellent efficiency in reducing losses and allowing light power propagation in optoelectronic devices [22].

A Multiphysics toolbox is used in this study to precisely model various shapes of SPPs on thin film solar cells. The contributions of this study are modeling five different shapes of SPPs, studying the effect of each shape on the efficiency of thin film solar cells, and extracting the equivalent circuit parameters for each one.

The remainder of the paper structured as follows, structure of models and parameters of used models in Section 2. Optical and electrical model in section 3. The effects of the simulation given in Sec. 4. Finally, our observations of our work are summarized in Section 5.

2.MODEL STRUCTURE AND PARAMETERS

The structure of the modeled solar cell as shown in Fig. 1, consisting of four stacked layers: a protective SiO₂ layer at the top and the a-Si layer absorbers as a P-I-N structure, followed by another SiO₂ layer at the rear, the whole layer structure constructed on top of the reflector behind. The intrinsic thickness of the amorphous silicon is 260 nm. In this paper, 40 nm thick layers N+ and P+ and 500 nm thick back reflector. The doping profile of P+ and N+ layers is $1 \times 10^{19} [cm^{-3}]$ and $1 \times 10^{19} [cm^{-3}]$ respectively.

Fig. 1 (b, c, d, e and f) shows the different SPPs shapes using gold simulated in this work to study the optical and electrical behaviors of the solar cell. Fig. 2 presents the doping profile of the used P-I-N layers.

Fig. 1. Structure of the P-I-N device of different types of **SPPs**, (a) without **SPP** [23], (b) square **SPP**, (c) trapezoidal **SPP**, (d) half circle **SPP**, (e) scalene triangle **SPP**, and (f) equilateral triangle **SPP**.

Fig. 2. The doping profile in **P-I-N device model** simulation for P-N device.

3. Mathematical model

3.1 The Excitation of SPP

SPPs will excite along with photons and electrons. The excitation with electrons is produced in the metallic mass as a result of exciting electrons. The light energy is distributed in plasma form [24] at the same time as the electrons are dispersed.

Aimed to rouse an SPP at a photon, they each have to have the same frequency and momentum. The free-space photon meant to be defined for such a frequency is stronger than the SPP momentum, since both have dissimilar dispersion relations. Such a disparity in momentum causes the photon in free space to pair directly from air to the SPP. The SPP can't produce energy in the dielectric as a free-space photon atop a smooth out metal surface, aimed for the same purpose. Such a misalignment refers to the lack of transmission that occurs through absolute inner reflection.

3.2 The Fields and dispersion relation in SPP

From Maxwell's equations, the SPP characteristics can be obtained. Here, $Z = 0$ at metal – dielectric interface, $Z < 0$ through the metal and $Z > 0$ through dielectric. As a function of position (x, y, z) and time t the electric and magnetic fields can be written as [25, 26],

$$E_{x,n}(x, y, z, t) = E_0 e^{ik_x x + ik_{z,n} |z| - i\omega t} \quad (1)$$

$$E_{z,n}(x, y, z, t) = \pm E_0 \frac{k_z}{k_{z,n}} e^{ik_x x + ik_{z,n} |z| - i\omega t} \quad (2)$$

$$H_{y,n}(x, y, z, t) = H_0 e^{ik_x x + ik_{z,n} |z| - i\omega t} \quad (3)$$

Where $\mathbf{n}$ refers to physical material (1 for $z < 0$ metal or 2 for $z > 0$ dielectric). The angular frequency of the waves is ω . $\pm$ is + to the metallic, $-$ to the dielectric. $\mathbf{E}_x, \mathbf{E}_z$ for the electric field vector are the x- and z- parts, $\mathbf{H}_y$ the magnetic field vector is the y- part, in addition to the other parts ($\mathbf{E}_x, \mathbf{E}_z, \mathbf{H}_y$) are zero. The SPPs are TM (transverse magnetic) waves forever. $\mathbf{K}$ is the wave vector; it is a compound vector, and when a lossless SPP occurs, it transforms the x parts into real and the z elements into imaginary elements-the wave fluctuates along the x path and exponentially in the z path. k_x is often the same as intended for the content when $k_{z,1}$ is usually different from $k_{z,2}$, where,

- $\frac{H_0}{E_0} = -\frac{\epsilon_1 w}{k_{z,1} c}$ or $\frac{H_0}{E_0} = -\frac{\epsilon_2 w}{k_{z,2} c}$, where ϵ_1 is permittivity of the metallic.

In subsequent equations, a wave of this structure fulfills Maxwell's equations in single state, or

$$\frac{k_{z,1}}{\epsilon_1} + \frac{k_{z,2}}{\epsilon_2} = 0 \quad (4)$$

And

$$K_x^2 + K_{zn}^2 = \epsilon_n \left(\frac{w}{c}\right)^2 \quad n = 1, 2 \quad (5)$$

Eq. (4) and Eq. (5) can be solved to obtain the dispersion relationship for a wave spreading at the top surface as,

$$k_z = \frac{w}{c} \left(\frac{\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2}\right)^{1/2} \quad (6)$$

The metal dielectric formula is obtained within the free electron model of the electron stream, which avoids reduction [27], or

$$\epsilon(w) = 1 - \frac{w_p^2}{w^2} \quad (7)$$

Where the frequency of plasma on SI units can be written as,

$$w_p = \sqrt{\frac{ne^2}{\epsilon_0 m^*}} \quad (8)$$

Here n is the electron density, e is the electron's charge, m^* is the electron's effective mass and ϵ_0 is the free-space permittivity. The SPP acts as a photon at low k , but the dispersion relationship bows and reaches an asymptotic boundary called the "surface plasma frequency" as it rises.

Similar to metal-SPP, it is sufficient to assume that the surface wave often induces metal-dielectric multilayer pairing between the electromagnetic field and electronic fluctuation [28]. This wave is confined to the metamaterial boundary and spreads alongside the interface. The electromagnetic field normally decreases exponentially according to the limited energy near the boundary and will not spread within the substantial. As shown in Fig.3, the thickness of the Plasmon blank substratum depends on the imaginary portion of the dielectric constant in thin films and its position is strengthened by the dint of the dielectric layer's wideness. From Fig. 3, the dispersion relationship varies and the angle is transferred as the thin dielectric layer is adsorbed to the top of the thin metal film sheet. This resonance angle swing is proportional to the optical thickness, which is influenced by the difference between each of the refractive indices and the depth of the thin film.

Fig.3 The dispersion relative to the photon through surface plasmon, as k grows the dispersion curve leans down and reaches the asymptotic limit [27].

3.3 The Propagation length and skin depth in SPP

So an SPP stretches the top lengthwise, because of the absorption it drops energy toward the metallic. The surface plasmon concentration falls off the square of the electric field, so at a distance x , the intensity decreased by the factor of $\exp\{-2k_x^{\epsilon}\}$ (x not subscript, as I believe). The length of propagation is expressed as the expanse to decline by a factor of $1/e$ to the SPP power. This condition is fulfilled to a degree [29]

$$L = \frac{1}{2k_x^{\epsilon}} \quad (9)$$

Similarly, the electric field evanescently decreases making it a corner to the top of the metallic. The SPP diffusion depth within this metal is typically calculated through the formulation of the skin depth at small frequencies. The field within the dielectric will slowly decrease further beyond. The measurements of decline within the metal and dielectric medium recorded in place of follows [30]

$$Z_i = \frac{\lambda}{2\pi} \left(\frac{|\epsilon'_1 + \epsilon_2|}{\epsilon_i^2} \right)^{1/2} \quad (10)$$

Where 'i' define propagation intermediate. SPPs are very sensitive to small skin depth disorders and as a result, SPPs are also used to examine top inhomogeneity.

3.4 Five-Parameter Model (single diode model)

The single-diode standard, as shown in the Fig. 4 consist of four main parameters as follows: the existing photovoltaic action source I_{ph} , and the diode itself. The ideal recombinant current of electrons and holes in cell-side diffusion and recombination (Shockley diffusion theory), R_{se} and R_{sh} accounting for various causes of loss and no ideals.

Fig. 4 Equivalent circuit of a solar cell [31].

Where:

$$R_s = \frac{V_{oc} - V_m}{10 \cdot I_m} \quad (11)$$

$$R_{sh} = \frac{10 \cdot V_m}{I_{sc} - I_m} \quad (12)$$

$$K_1 = \frac{R_{sh} - R_s}{R_s} \cdot \left[\frac{I_m \cdot (R_{sh} + R_s) - V_m}{V_m - I_m \cdot R_s} \right] \quad (13)$$

$$n = \frac{V_m + R_s \cdot (I_m - I_{sc})}{V_t \cdot \ln(K_1)} \quad (14)$$

$$I_0 = \frac{R_s \cdot n \cdot V_t}{R_{sh} \cdot (R_{sh} - R_s)} \cdot \exp \left[\frac{-I_{sc} \cdot R_s}{n \cdot V_t} \right] \quad (15)$$

$$I_{ph} = I_{sc} + I_0 \cdot \left[\exp \frac{I_{sc} \cdot R_s}{n \cdot V_t} - 1 \right] + \frac{I_{sc} \cdot R_s}{R_{sh}} \quad (16)$$

Where I_0 is the diode's reverse saturation current, n is a non-dimensional constant called the ideality factor that defines the diode's deviation from the Shockley diffusion principle, V_{oc} and I_{sc} are respectively the open circuit voltage and the short circuit current [31]. Ultimately, the thermal stress is V_t .

The main electrical parameters for the solar cell such as solar cell output, open circuit voltage, and short circuit current [32, 33] can be extracted from our simulation-based model.

$$\text{Solar Cell Efficiency}(\%) = \frac{I_{sc} V_{oc} FF}{P_{in}} \quad (17)$$

FF is the filling factor, which can derived from J–V curve of the device as,

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}} \quad (18)$$

4. P-I-N DEVICE SIMULATION RESULTS

4.1 Optical parameters simulation Results

Fig. 5 shows the results for simulating the propagation of the electrical field in the x and y direction of certain structures. In the cross-sectional area Fig. 5a, the effect of electric field strength on the silicone substrate for a typical PIN-device without the SPP is indicated. For SPP-free thin film solar cell. Fig. 5f the light intensity across the SPP is visible along the aperture, when the electric field intensity is maximized, because the incident light helps electrons swap their unique features like plasmon polaritons with the help of the Au SPP Fig. 5f The thin film solar cell with equilateral SPP triangularity. In Fig. 5a, 5f at the right up it can be observed from the electric field intensity figure that there is an enhancement using Au SPP.

Fig. 5. The electric field in different shapes of SPPs, (a) without, and (f) equilateral triangle SPP.

4.1 Electrical parameters simulation Results

The results of the simulation for this P-I - N device model, as shown in Figure 6 and Table 1, as well as power curves for the presented models with different forms of SPPs, provide complete details about the output data presented. In the case of an efficiency without an SPP of 13.69 %, a little more of the efficiency between the previous two models for a rectangle SPP was 14.47 %. However, the efficiency for trapezoidal PSP was 14.44%, with a further small improvement of around 0.45% for half-circle SPP. The best result in this analysis was 14.76 % for the equilateral SPP triangle, with an average increase of 1.07 % between the first and last iterations.

Fig. 6. J-V / P-V curve in **P-I-N device model** with different types of surface grating, (a) without SPP, (b) square SPP, (c) trapezoidal SPP, and (d) half circle SPP, and (f) equilateral triangle SPP.

The Top SPP triangle uses the scatter effects to allow a lighter penetration into the solar cell, thereby maximizing overall absorption and electrical power over the other grid, as illustrated in Table 1. The rear reflector of the thin-film solar cell reflects and disperses light that not absorbed in the first phase through the membranes. The shapes and the sizing of the SPP are based on the cell's diffraction of the incident solar spectrum, determining the amount of power produced by the cell. When the back reflector substrate is added at the bottom of the structure, the unabsorbed photons are also redirected to a P-I - N junction, optimizing light entanglement and increasing solar efficiency. We look at the spectrum, because it has an effect of 0.843 in the equilateral triangle SPP on total electricity generated from the solar cell. For whole cases, the solar cell 's maximum absorbed power is increased by 14,65[mW] regardless of the position of proposed equilateral SPP triangle.

Table 1. The result values of **P-I-N** device.

Parameter Name	Without SPP	Rectangle SPP	Trapezoidal SPP	Half-Circle SPP	scalene Triangle SPP	Equilateral Triangle SPP	Equilateral Triangle grating [6]
P_{in} [W/m ²]	1000	1000	1000	1000	1000	1000	1000
P_{max} [mW]	13.7	14.5	14.35	14.1	14.6	14.7	12.5
J_{sc} [mA/cm ²]	17.75	18.8	18.7	18.3	19.1	19.2	13
V_{oc} [V]	0.93	0.933	0.932	0.931	0.934	0.935	1.08
J_m [mA/cm ²]	16.7	17.65	17.6	17.15	17.9	18	12.5
V_m [V]	0.82	0.82	0.82	0.82	0.82	0.82	0.98
FF	0.829	0.825	0.828	0.823	0.82	0.822	0.872
Efficiency (%)	13.69	14.47	14.43	14.06	14.67	14.76	12.25
n	3.34	3.38	3.34	3.42	3.43	3.40	3.56
I_0 [A]	1.2E-06	9.23E-08	8.32E-08	1.03E-07	1.10E-07	1.00E-07	1.562E-8
I_{ph} [A]	0.0177	0.0188	0.0187	0.0183	0.0191	0.0192	0.013
R_s [Ω]	0.658	0.640	0.636	0.674	0.636	0.638	0.800
R_{sh} [Ω]	780	713	745	638	656	683	1960

At the rest of Table 1 we summarized the calculated values for the PV electrical parameters (I_0 , I_{ph} , R_s , and R_{sh}). It is noticed that the electrical parameters are enhanced definitely for equilateral triangle SPP based technique. The last column in Table 1 shows the results of Ref. [6] by compare it with the simulated model at the case of equilateral triangle SPP the observation is more enhancement in Efficiency and R_s about 2.51% and 25% respectively.

5. CONCLUSIONS

In this paper, both electrical and optical characteristics of the thin film solar cells are examined. Various SPPs shaped in order to increase the absorption rate and related dimensions are studied. The SPPs generally improved photovoltaic efficiency besides the maximum output power compared to the thin film solar cells. A significant improvement are achieved for triangle shaped SPPs based thin film solar cells. The best results of this analysis for the SPP triangle were 14.76%, the total performance change between the first and last versions was 1.7%. In the SPP equilateral triangle, we also consider the spectrum because it affects total power generated by the solar cell and a fill factor of 0.822. Finally we observed that the location of equilateral triangle SPP the maximum power absorbed by the solar cell is enhanced by 14.7[mW]. The R_s value improved by about 3 % for the equilateral SPP triangle.

6.

Author Contribution All the authors have contributed equally.

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Declarations

Consent to Participate All the authors agreed to involve in this research work.

Consent for Publication All the authors have given permission to publish the results.

Conflict of Interest The authors declare that they have no conflict of interest.

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Figures

Figure 1

Structure of the P-I-N device of different types of SPPs, (a) without SPP [23], (b) square SPP, (c) trapezoidal SPP, (d) half circle SPP, (e) scalene triangle SPP, and (f) equilateral triangle SPP.

Figure 2

The doping profile in P-I-N device model simulation for P-N device.

Figure 3

The dispersion relative to the photon through surface plasmon, as k grows the dispersion curve leans down and reaches the asymptotic limit [27].

Figure 4

Equivalent circuit of a solar cell [31].

Figure 5

The electric field in different shapes of SPPs, (a) without, and (f) equilateral triangle SPP.

Figure 6

J-V / P-V curve in P-I-N device model with different types of surface grating, (a) without SPP, (b) square SPP, (c) trapezoidal SPP, and (d) half circle SPP, and (f) equilateral triangle SPP.