The effect of different surface plasmon polariton shapes on thin-film solar cell efficiency

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Abstract
The effects of surface plasmon polaritons (SPPs) on the efficiency, series resistance, and shunt resistance of thin-film Si solar cells are studied and analyzed in this work. Different SPP shapes and their effects on the optical and electrical properties and thereby the efficiency of thin-film solar cells are studied. Semiconductor and electromagnetic models are incorporated to study the electrical and optical behaviors of the thin-film solar cells, respectively, using COMSOL Multiphysics three-dimensional (3D) numerical simulation software. An efficiency of 14.76% is achieved for triangular SPPs, representing a 1.07% improvement compared with SPP-free solar cells. The solar cell electrical parameters are also extracted based on a single-diode equivalent model. The series resistance is decreased by 3% for solar cells having equilateral-triangle SPPs compared with SPP-free solar cells.

Keywords Thin-film Si solar cells · Surface plasmon polaritons · Efficiency improvement

1 Introduction
Photovoltaic technology is the cleanest way to generate electrical energy, based on the conversion of solar energy [1]. The increasing demand for higher photovoltaic efficiency is the main challenge facing increasing application of solar cells to enable mass production and thereby decrease their cost. This is due to the high cost of the materials and process, which is certainly the case for solar cells based on bulk silicon [2].

Thin-film solar cells enabled reduced cost by replacing the bulk substrate with thin-film layers. The main issue when using such thin-film technology is the reduction of the absorption threshold to the energy gap of the semiconductor material. Thin-film silicon solar cells offers various advantages but still required enhanced efficiency and improved production methods. Thin-film silicon solar cell technology has challenged crystalline silicon cells recently through its use of a limited amount of active materials and record low-temperature growth, although crystalline silicon solar cells grow rapidly in thin-film form [3–6].

Plasmonic-based solar cells represent an excellent option for increasing the efficiency and improving the manufacturing procedures [7]. The utilization of metallic nanostructures that support surface plasmons is a novel approach to achieve light trapping in thin-film solar cells [8]. Excitation of conduction electrons at the interface between a metal and dielectric may focus and reflect light into the thin semiconductor layer, thereby increasing its absorption. Such surface plasmons produced in metal nanoparticles as well as surface plasmon polaritons (SPPs) propagating at the metal–semiconductor interface are both of interest in this regard[9].

In recent years, many literature studies have used various plasmonic structures to enhance the efficiency of thin-film solar cells. Finite-element analysis has also been used to explore the effect of different Au grating structures on the absorption of light in solar cells. This solar cell geometry consists of a Au layer on an amorphous silicon (a-Si)
substrate. The periodicity of the grating device is designed in such a way that surface plasmon polaritons (SPPs) are excited [10].

Another technique, using a different plasmonic structure, combines silver nanoparticles with a silicon thin-film solar cell [11]. The goal of this structure is to allow sunlight to penetrate the cell at any angle with the minimum reflection. Silicon acts as the absorbing layer, and its molecular bonds break down and release many electrons because of their high absorption rate when sunlight enters this layer. Spherical silver nanoparticles are also located in this layer to increase the absorption of solar energy via localized plasmon resonance on the surface [11].

Gratings can also be applied to generate such a plasmonic effect, in particular by introducing a plasmonic grating on the surface of the solar cell to control the absorption, manipulate, and detect light with a specific polarization. Such a plasmonic grating can contribute to increase the absorption and result in excellent efficiency by reducing losses and allowing the propagation of light in optoelectronic devices [12]. In this work, an efficient strategy for improving the efficiency of thin-film solar cells by utilizing a plasmonic grating structure at the rear electrode or back metal contact is presented and analyzed. The light is diffracted by the grating surface, which increases the path length of the reflected light. Additionally, the energy of the solar plasmons excited within the grooves is related to the absorber layer. This effective light trapping strategy and the surface plasmon resonance effect both boost the absorption in the absorber layer of the solar cell, thus increasing the efficiency [13].

In this work, 3D numerical simulations are applied to precisely model SPPs with various shapes on thin-film solar cells. The contributions of this paper are to model five different shapes of SPPs, study the effect of each on the efficiency of the thin-film solar cell, and extract the equivalent circuit parameters for each.

The remainder of this paper is structured as follows: The structures and parameters used throughout this paper are described in Sect. 2. The optical and electrical model are introduced in Sect. 3. The simulation results and remarks are explored in Sect. 4. Finally, observations based on this work are summarized in Sect. 5.

2 The model structure and parameters

The typical structure of a solar cell is shown in Fig. 1a, comprising four stacked layers of (1) a protective SiO2 layer at the top, (2) an a-Si absorption layer with a PIN structure, (3) an SiO2 layer at the rear, and (4) the whole layer structure constructed on top of a reflector behind.

Figure 1b–f shows the proposed structures with different grating shapes considered in this work. The new structures are obtained from the typical one shown in Fig. 1a. The gold layer is part of the grating structure layer. The proposed structures are classified according to the applied shapes as free of SPPs (Fig. 1a), rectangular (Fig. 1b), trapezoidal (Fig. 1c), semicircle (Fig. 1d), scalene triangle (Fig. 1e), and equilateral triangle (Fig. 1f). Note that the dimensions of the proposed structures are shown on the corresponding figure.

The dimensions for the SPPs are clearly shown in Fig. 1, while the horizontal spacing between the SPP gold layers is 30 nm. The model parameters used throughout this work are presented in Table 1.

Figure 2 shows the doping profile of the PIN layers used in this work. The N++ layer is doped to 1 × 10^{19} atom/cm^3 and reaches 1 × 10^{18} atom/cm^3 along the layer thickness, according to the process variation; abruptly doping cannot be created, so we created a very thin doped layer of 20 nm of 10^{18} atom/cm^3 (the same being introduced for the P++ layer). An intrinsic layer with a thickness of 260 nm separates the two doped layers.

3 The mathematical model of the SPPs

3.1 The excitation of the SPPs

SPPs, like photons and electrons, can be excited. An excitation with electrons occurs in the bulk metal because of electrons being excited. At the same time, as the electrons spread, the light energy diffuses in the form of plasma [15].

For an SPP to excite more photons, each must have the same frequency and momentum. The momentum of a free-space photon with such a frequency is greater than that of the SPP because of their dissimilar dispersion relations. This momentum difference means that the free-space photon can transfer directly from air to the SPP. Unlike a free-space photon on top of a smooth metal surface, the SPP cannot produce energy in the dielectric. This discrepancy prevents transmission via total internal reflection.

3.2 The fields and dispersion relation in SPP

The characteristics of the SPP can be obtained from Maxwell’s equations. Here, Z = 0 at the metal–dielectric interface, Z < 0 through the metal, and Z > 0 through the dielectric. As a function of position (x, y, z) and time t, the electric and magnetic fields can be written as [16, 17],

\[ E_{x,y,z}(x, y, z, t) = E_0 e^{ik_x x + ik_y y + ik_z z} e^{-iwt}, \]

\[ E_{z,y,z}(x, y, z, t) = \pm E_0 \frac{k_z}{k_{z,0}} e^{ik_x x + ik_y y + ik_z z} e^{-iwt}, \]
where \( n \) refers to the physical material (1 for \( z < 0 \) in the metal or 2 for \( z > 0 \) in the dielectric). The angular frequency of the waves is \( \pm \omega \), where the plus sign applies to the metal and the minus sign to the dielectric. \( E_x \) and \( E_z \) are the \( x \)- and \( z \)-components of the electric field vector, while \( H_y \) is the \( y \)-component of the magnetic field vector, while the other parts \((E_x, E_z, H_y)\) are zero. The SPPs are always transverse magnetic (TM) waves. \( K \) is the wavevector; it is a compound vector, and when a lossless SPP occurs, it transforms the \( x \) parts to real and the \( z \) elements to imaginary elements, while the wave oscillates along the \( x \) direction and varies exponentially in the \( z \) direction. \( k_z \) is the same as intended for the content when \( k_{z,1} \) is usually different from \( k_{z,2} \).

\[
H_{y,m}(x, y, z, t) = H_0 e^{ik_x x + ik_{z,m} |z| - i \omega t},
\]

In subsequent equations, a wave with this structure fulfills Maxwell’s equations in a single state, or

\[
\frac{H_0}{\varepsilon_0} = -\frac{\varepsilon_{1w}}{\varepsilon_{1c}} \text{ or } \frac{H_0}{\varepsilon_0} = -\frac{\varepsilon_{2w}}{\varepsilon_{2c}} \quad \text{where } \varepsilon_1 \text{ is the permittivity of the metal. } E_0 \text{ and } H_0 \text{ can be interpolated to account for the different shapes of grating, since both the magnitude and direction of the electric field and magnetic field can be controlled via the wall geometry of the SPPs.}
\]

In subsequent equations, a wave with this structure fulfills Maxwell’s equations in a single state, or

\[
\frac{k_{z,1}}{\varepsilon_1} + \frac{k_{z,2}}{\varepsilon_2} = 0,
\]

Fig. 1 The structure of the PIN device with different types of SPP: a none [14], b rectangular, c trapezoidal, d semicircle, e scalene triangle, and f equilateral triangle.
Equations (4) and (5) can be solved to obtain the dispersion relationship for a wave spreading at the top surface as

$$k_z = \frac{w}{c} \left( \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2} \right)^{1/2}. \quad (6)$$

The metal dielectric formula is obtained within the free electron model of the electron stream, which avoids damping [18], or

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

where the plasma frequency can be written in SI units as

$$w_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m^*}}. \quad (8)$$

Here $n_e$ is the electron density, $e$ is the electron charge, $m^*$ is the electron's effective mass, and $\varepsilon_0$ is the free-space permittivity. The SPP acts as a photon at low $k$, but the dispersion relationship bends over and reaches an asymptotic boundary called the “surface plasma frequency” as it rises.

Similar to a metal SPP, it is sufficient to assume that the surface wave often induces metal–dielectric multilayer pairing between the electromagnetic field and electronic fluctuation [19]. This wave is confined to the metamaterial boundary and spreads along the interface. The electromagnetic field normally decreases exponentially according to the limited energy near the boundary and will not spread within the bulk. As shown in Fig. 3, the thickness of the plasmon blank substratum depends on the imaginary part of the dielectric constant in the thin film, and its position is

Table 1: The value of each of the parameters

| Parameter                                      | Value                             |
|------------------------------------------------|-----------------------------------|
| $T$ (temperature)                              | 300 (K)                           |
| Anode doping ($P^+$ doping)                    | $1 \times 10^{19}$ (1/cm$^3$)    |
| Cathode doping ($N^+$ doping)                  | $1 \times 10^{19}$ (1/cm$^3$)    |
| a-Si, intrinsic carrier concentration          | $1.5 \times 10^{10}$ (1/cm$^3$)  |
| Thickness (I, Si)                              | 260 nm                            |
| Thickness ($N^+$, Si)                          | 40 nm                             |
| Thickness ($P^+$, Si)                          | 40 nm                             |
| Thickness (SiO$_2$)                            | 75 nm                             |
| Angle of incidence                             | 0 (°)                             |
| a-Si, electron mobility                        | 1500 cm$^2$/V-s                  |
| a-Si, hole mobility                            | 450 cm$^2$/V-s                   |
| a-Si intrinsic, electron carrier lifetime      | 20 ns                             |
| a-Si intrinsic, hole carrier lifetime           | 20 ns                             |
| a-Si $N^+$, electron carrier lifetime          | 0.0001 ns                         |
| a-Si $N^+$, hole carrier lifetime              | 10 ns                             |
| a-Si $P^+$, electron carrier lifetime          | 10 ns                             |
| a-Si $P^+$, hole carrier lifetime              | 0.0001 ns                         |
| Back reflector (silver)                        | 500 nm                            |
| Input power flow                               | 100 mW/cm$^2$                     |
| Si, bandgap at 300 K                           | 1.74 eV                           |
| Si, electron affinity                          | 4.00 eV                           |
| Si, relative permittivity                      | 11.7                              |

and

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

Fig. 2 The doping profile used in the PIN device model simulations
strengthened by the dint of the dielectric layer's wideness. As shown in Fig. 3, the dispersion relation varies and the angle changes when the thin dielectric layer is adsorbed to the top of the thin metal film sheet. This swing in the resonance angle is proportional to the optical thickness, which depends on the difference between the refractive indices and depth of the thin film.

3.3 The propagation length and the skin depth in the SPP

The SPP stretches the top lengthwise, because the absorption causes energy transfer toward the metal. The surface plasmon concentration falls off as the square of the electric field, so at a distance \( x \), the intensity is decreased by a factor of \( \exp(-2k''x) \). The propagation length can be expressed as the length corresponding to a decrease in the SPP power by a factor of \( 1/e \). This condition is fulfilled at a length of \( 20 \)

Similarly, the electric field decreases evanescently, forming a corner at the top of the metal. The SPP diffusion depth within the metal is typically calculated using the formula for the skin depth at low frequencies. The field within the dielectric will decrease slowly beyond this. The decreased recorded within the metal and dielectric medium is as follows \( 21 \)

\[
Z_i = \frac{\lambda}{2\pi} \left( \frac{|\varepsilon_1 + \varepsilon_2|}{\varepsilon_i^2} \right)^{1/2},
\]

where \( i \) indexes the propagation medium. SPPs are very sensitive to small skin depth variations and can thus also used to examine the inhomogeneity of the top surface.

3.4 The five-parameter (single-diode) model

The single-diode model (Fig. 4) includes the following four main parameters: the photovoltaic current source \( I_{ph} \), the diode itself, and the ideal electron–hole recombination current due to cell-side diffusion and recombination (according to Shockley diffusion theory), with \( R_{se} \) and \( R_{sh} \) accounting for various causes of loss and nonideality.

- \( R_s = \frac{V_{oc} - V_m}{10 \cdot I_m} \), \( R_{sh} = \frac{10 \cdot V_m}{I_{sc} - I_m} \),
- \( K_1 = \frac{R_{sh} - R_s}{R_s} \cdot \frac{V_m}{I_m \cdot n^i} \),
- \( n = \frac{V_m + R_s \cdot (I_m - I_{sc})}{V_t \cdot \ln(K1)} \),
- \( I_0 = \frac{R_s \cdot n_i \cdot V_t}{R_{sh} \cdot (R_{sh} - R_s)} \cdot \exp \left[ \frac{-I_{sc} \cdot R_s}{n \cdot V_t} \right] \),
- \( I_{ph} = I_{sc} + I_0 \cdot \left[ \exp \left( \frac{I_{sc} \cdot R_s}{n_i \cdot V_t} - 1 \right) + \frac{I_{sc} \cdot R_s}{R_{sh}} \right] \),

where \( I_0 \) is the reverse saturation current of the diode, \( n_i \) is a nondimensional constant called the ideality factor that defines the diode’s deviation from the Shockley diffusion principle, \( I_m \) and \( V_m \) are the values of \( I \) and \( V \) at the maximum power point, and \( V_{oc} \) and \( I_{sc} \) are the open-circuit voltage and short-circuit current, respectively \( 22 \), while the thermal stress is \( V_t \).

The main electrical parameters for the solar cell, such as the solar cell output, open-circuit voltage, and short-circuit...
current [23], can be extracted from this simulation-based model.

\[
\text{Solar cell efficiency(%) = } \frac{J_{sc} V_{oc} \text{ FF}}{P_{in}},
\]

where FF is the fill factor, which can be derived from the \(J-V\) characteristic of the device as

\[
\text{FF} = \frac{I_m V_m}{I_{sc} V_{oc}}.
\]

4 The simulation results for the PIN device

4.1 The simulation results for the optical parameters

Figure 5 shows the simulation results obtained for an electrical field with a wavelength of 870 nm in the \(x\)- and \(y\)-direction for the typical and equilateral-triangle SPP structures. Figure 5a shows the effect of the electric field strength on the silicon substrate for a typical PIN device without the SPP. The simulation results in Fig. 1a, f show the electric field intensity across the SPP along the aperture. As shown in Fig. 5f, the electric field intensity was enhanced at the end of the \(P++\) layer because of the equilateral-triangle SPP gold layer.

Figure 5a, f (upper right) shows the electric field intensity, revealing an enhancement when using the Au SPP.

4.2 The simulation results for the electrical parameters

Figure 6 and Table 2 show the simulation results for the electrical behavior of the PIN thin-solar cell with and without SPPs. Note that the efficiency of the thin-film solar cell without the SPP structure reaches 13.69\%. Meanwhile, the thin-film solar cell with the SPP grating achieves efficiency values of 14.06\%, 14.43\%, 14.47\%, 14.67\%, and 14.76\% for the semicircle, trapezoidal, rectangular, scalene-triangle, and equilateral-triangle SPPs, respectively. The highest efficiency is thus obtained for the equilateral-triangle SPPs, reaching about 14.76\%, higher than the value for the thin-film solar cell without SPPs by 1.07\%.

The top SPP triangle uses scattering effects to enable less penetration into the solar cell, thereby maximizing the overall absorption and electrical power over the rest of the grid, as illustrated in Table 2. The rear reflector of the thin-film solar cell reflects and disperses light that is not absorbed in the first pass through the films. The shape and size of the SPP are based on the diffraction of the solar spectrum incident on the cell, thus determining the

![Electric field intensity with Cell depth](image)

Fig. 5 The electric field for the SPPs with different shapes: a without and f with the equilateral-triangle SPP

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amount of power produced by the cell. When the back reflector substrate is added at the bottom of the structure, unabsorbed photons are also redirected to a PIN junction, thus optimizing the light absorption and increasing the solar efficiency. Looking at the spectrum, the equilateral-triangle SPP has an effect of 0.843 on the total electricity generated by the solar cell. For all the studied cases, the maximum power absorbed by the solar cell is increased by 14.65 mW, regardless of the position of the proposed equilateral-triangle SPP.

The remainder of Table 2 summarizes the values calculated for the PV electrical parameters ($I_0$, $I_{ph}$, $R_s$, and $R_{sh}$). Note that the electrical parameters are enhanced when using the equilateral-triangle SPP-based. The final column in Table 2 shows the results from Ref. [6] for comparison with the current simulation results. In the case of the equilateral-triangle SPP, this comparison reveals an enhancement in efficiency and $R_s$ by about 2.51% and 25%, respectively.

### Table 2 The results for the PIN device

| Parameter | Without SPP | Rectangle SPP | Trapezoidal SPP | Semicircle SPP | Scalene-triangle SPP | Equilateral-triangle SPP | Equilateral-triangle grating [6] |
|-----------|-------------|---------------|----------------|---------------|----------------------|--------------------------|-------------------------------|
| $P_{in}$ (W/m²) | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 |
| $P_{max}$ (mW/cm²) | 13.7 | 14.5 | 14.35 | 14.1 | 14.6 | 14.7 | 12.5 |
| $J_{sc}$ (mA/cm²) | 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 |
| $I_{m}$ (mA/cm²) | 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 |
| $n_i$ | 3.34 | 3.38 | 3.34 | 3.42 | 3.43 | 3.40 | 3.56 |
| $I_0$ (A) | $1.2 \times 10^{-6}$ | $9.23 \times 10^{-8}$ | $8.32 \times 10^{-8}$ | $1.03 \times 10^{-7}$ | $1.10 \times 10^{-7}$ | $1.00 \times 10^{-7}$ | $1.562 \times 10^{-8}$ |
| $I_{ph}$ (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 |

Fig. 6 The $J–V$/$P–V$ characteristics of the PIN device model with different types of surface grating: a none, b square, c trapezoidal, d semicircle, and f equilateral-triangle SPP.

The J–V/P–V characteristics of the PIN device model with different types of surface grating: a none, b square, c trapezoidal, d semicircle, and f equilateral-triangle SPP.
5 Conclusions

Both the electrical and optical characteristics of thin-film solar cells are examined. Three-dimensional numerical analysis is carried out using COMSOL Multiphysics software, incorporating semiconductor and electromagnetic models to study the electrical and optical behavior, respectively. The optical behavior of the solar cells with shaped SPPs, including the absorption rate and related dimensions, are studied. The introduction of SPPs generally improves the photovoltaic efficiency as well as the maximum output power compared with standard thin-film solar cells. A significant improvement is achieved for the thin-film solar cells based on triangle-shaped SPPs. An efficiency value of 14.76% is obtained for the thin-film solar cell with equilateral-triangle SPPs, being higher than the value for the grating-free thin-film solar cell by 1.7%. The series resistance is also improved, being decreased by about 3% for the thin-film solar cell with equilateral-triangle SPPs, which enhances the electrical properties such as the open-circuit voltage and thereby the efficiency of the solar cell.

Authors' contributions All authors contributed equally.

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Data availability Data related to this article are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

Consent to participate All the authors agreed to be involved in this research work.

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

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