

## *Investigating the Influence of Temperature Variations on the Performance of Surface Plasmon-Enhanced Thin Film Solar Cells*

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**Abstract:** Advancements in the realm of solar energy conversion are pivotal as we seek to unlock the full potential of renewable energy sources. A fundamental challenge lies in enhancing the absorption of sunlight, spanning both the visible and infrared spectra, which holds the key to boosting overall efficiency. In this quest, surface plasmons (SPPs) have emerged as highly promising agents. A substantial body of literature has probed the myriad geometries of SPPs, meticulously investigating their influence on both optical and electrical characteristics, with a particular focus on their application in thin-film solar cells. Among these configurations, triangular SPPs have demonstrated exceptional promise, showing the potential to deliver optimal outcomes. The primary objective of this study is to delve into the intricate relationship between temperature variations and the performance of triangular SPPs, each measuring a diminutive  $10 \times 10$  nm. We have undertaken a rigorous examination of key electrical parameters that include the short-circuit current, open-circuit voltage, series resistance, parallel resistance, and, crucially, overall efficiency. This investigation leverages the sophisticated capabilities of COMSOL Multiphysics, a state-of-the-art three-dimensional (3D) numerical simulation platform. By employing this cutting-edge tool, we can comprehensively explore the intricate interplay between semiconductor properties and electromagnetic phenomena. The findings that emerge from these simulations reveal an intriguing trend. As the temperature surpasses the critical threshold of 300 K, we observe a discernible decrease in the efficiency of the triangular SPPs. This observation underscores the vital role played by temperature in the performance of these plasmonic structures, shedding light on a previously understudied dimension in our ongoing pursuit of enhanced solar energy conversion efficiency. These insights represent a significant stride forward, paving the way for the development of nuanced strategies in the design and practical implementation of SPP-based solar energy conversion technologies. This progress brings us one step closer to realizing a sustainable energy future, where solar power stands as a robust and reliable source of clean energy.

**Keywords** Thin film solar cells, Surface plasmons, Solar cell efficiency, Reverse saturation current, Temperature effect.

## 1. Introduction

Photovoltaic technology stands at the forefront of sustainable energy solutions, capitalizing on the remarkable capability of solar cells to transform sunlight into clean and cost-effective electricity. The energy harnessed through photovoltaics embodies the quintessential qualities of being both renewable and environmentally benign. As global awareness of the imperative to transition to clean energy sources intensifies, the demand for solar energy continues to surge exponentially [1, 2]. However, this fervent quest for solar energy adoption presents a multifaceted challenge: the pursuit of superior photovoltaic efficiency.

In the context of enhancing photovoltaic efficiency, thin-film solar cells have emerged as a transformative approach. These innovative devices are strategically designed to curtail costs, thereby circumventing the economic constraints associated with traditional silicon-based solar cells. Silicon cells necessitate large-scale production, which invariably translates to substantial expenses. The solution to this conundrum lies in the integration of thin-film layers, effectively minimizing the utilization of the bulky silicon matrix [3, 4]. The principal objective behind this paradigm shift is to optimize the absorption of solar energy while mitigating the associated material and production costs.

Despite the inherent advantages offered by silicon solar films, there remains a compelling need for continued refinement and innovation in this domain. The journey towards harnessing the full potential of thin-film technology demands ongoing research and development efforts aimed at achieving superior results. Furthermore, the streamlining of current production methods represents an essential facet of this transformative process [5-8]. In this academic pursuit, we aim to delve deeper into the intricate dynamics of thin-film solar technology, exploring avenues for further advancement, and unlocking the latent potential of these revolutionary photovoltaic devices.

This endeavor holds the promise of not only optimizing the efficiency of photovoltaic systems but also contributing significantly to the global transition towards sustainable and renewable energy sources. The path ahead is challenging, yet the rewards are monumental, as we work collectively to shape a cleaner and more sustainable energy future.

Recent strides in the realm of thin-film silicon solar technology have given rise to a novel breed of crystalline silicon cells, marking a pivotal development in the photovoltaic landscape. This innovation revolves around the judicious utilization of reduced material quantities and lower thermal growth requirements. Notably, crystalline silicon-based solar cells have witnessed a burgeoning adoption in thin-film configurations, underscoring their remarkable potential [9-11]. As we stand at the cusp of a solar energy revolution, the pursuit of enhanced manufacturing processes becomes paramount. In this context, plasma-based solar cells have emerged as one of the most promising avenues for optimizing and elevating the efficiency of thin-film solar cells.

A groundbreaking approach in this endeavor involves the integration of metal nanostructures to bolster the phenomenon of surface plasmons, thereby revolutionizing the capture of light within thin-film solar cells [9-12]. This pioneering technique capitalizes on the excitation of conduction electrons occurring at the intricate junction between the metal and the dielectric interface. This excitation engenders a profound impact on incident light, focusing and redirecting it back into the thin semiconductor layer. Consequently, this process serves to augment the light output of the solar cell, translating into improved energy harvesting efficiency.

It is crucial to note that both metal nanoparticles, which foster the generation of localized surface plasmons, and surface plasmons propagated along metal-semiconductor interfaces, constitute indispensable facets of this innovative approach [12]. This multidimensional utilization of surface plasmons holds the promise of unlocking unprecedented levels of efficiency in thin-film silicon solar cells. In the realm of photovoltaic technology, this transformative breakthrough signifies a monumental step forward in our quest to harness the inexhaustible power of the sun. The amalgamation of thin-film silicon, plasma-based methodologies, and surface plasmon resonance stands as a testament to human ingenuity and our unwavering commitment to shaping a sustainable energy future. As we delve deeper into this evolving field, we anticipate further breakthroughs that will elevate the efficiency of solar energy conversion, propelling us towards a cleaner and more sustainable world.

As part of our ongoing academic inquiry into the optimization of thin-film solar cell performance, a rigorous literature review has unveiled a compelling trend—the pervasive use of plasmonic structures to enhance the efficiency of these solar cells. This review not only reaffirms the significance of plasmonics in the realm of photovoltaics but also emphasizes the diversity of strategies employed to harness their potential. Concurrently, finite element analysis (FEA), a powerful computational tool, has been harnessed to explore the performance of various temperature models and their profound impacts on light absorption within solar systems. This investigation focuses on a specific solar cell configuration comprising a gold layer atop an amorphous silicon (a-Si) substrate, where the periodicity of the grid material has been meticulously tailored to facilitate the excitation of surface plasmon polaritons (SPPs) [7]. Within the burgeoning field of thin-film solar cell technology, plasmonic structures have emerged as a focal point of research. These structures, designed to manipulate light-matter interactions, offer a promising avenue for augmenting the efficiency of solar energy conversion. The literature review showcases a diverse array of plasmonic strategies, including but not limited to nanoscale metal particles, nanoantennas, and metamaterials, each uniquely tailored to exploit the principles of plasmonics. By intricately engineering these structures, researchers have unlocked innovative pathways towards achieving enhanced light absorption and energy conversion within thin-film solar cells.

The application of finite element analysis (FEA) has been instrumental in advancing our understanding of temperature models and their intricate influence on light absorption in solar

systems. Through FEA, researchers have meticulously scrutinized the performance of these models, enabling a nuanced examination of temperature-induced effects on photovoltaic efficiency. This computational approach has empowered researchers to optimize temperature conditions, thus enhancing the overall performance of thin-film solar cells. The solar cell architecture under investigation is characterized by a gold layer superimposed onto an amorphous silicon (a-Si) substrate. This configuration has been carefully designed to exploit the benefits of surface plasmon polaritons (SPPs). The periodicity of the grid material plays a pivotal role in this setup, acting as a catalyst for the generation and manipulation of SPPs. By strategically tailoring this periodicity, researchers have sought to maximize the absorption of incident light, thereby elevating the energy conversion efficiency of the thin-film solar cell.

The integration of plasmonic structures and finite element analysis has ushered in a new era of innovation in thin-film solar cell technology. The marriage of plasmonics and computational analysis not only deepens our understanding of light absorption and energy conversion but also opens the door to groundbreaking advancements in renewable energy. As we continue to explore the synergistic possibilities of these approaches, we stand at the precipice of a sustainable energy revolution, poised to make a substantial impact on our global energy landscape.

In our quest to unlock the full potential of thin-film solar cells, recent research, notably presented in [13], has delved into a spectrum of plasmonic models. These investigations revolve around the integration of silver nanoparticles with silicon thin-film solar cells, driven by the overarching goal of enabling efficient sunlight absorption from various angles while minimizing reflective losses. Central to this innovative approach is the strategic deployment of silicon as the absorber material, leveraging its unique properties characterized by the disruption of molecular bonds and the release of numerous electrons upon exposure to sunlight. This inherent high absorption capacity forms the cornerstone for maximizing energy capture within the silicon layer. An intriguing facet of this research entails the utilization of spherical silver nanoparticles, strategically employed to amplify sunlight absorption through the phenomenon known as plasmon resonance. By adorning the surface with these nanoparticles, the solar cell's ability to capture incident light is significantly enhanced. The interaction between sunlight and these nanoparticles induces resonant oscillations of free electrons, culminating in heightened energy absorption. This innovative coating mechanism, underpinned by plasmonics, represents a pivotal stride toward improving the overall efficiency of thin-film solar cells [13-16].

Further advancements are achieved by introducing plasmonic grids onto the surface of the solar panel. These grids act as enablers of plasmonic effects, offering a multifaceted approach to light absorption, control, and capture, with a particular emphasis on polarization-specific light. This ingenious integration of plasmonic grids facilitates absorption processes, thereby leading to exceptional solar cell performance. Beyond reducing energy loss through reflection, it allows for the precise manipulation and direction of light, making it a pivotal tool in the realm of optoelectronic devices. This dual role of the plasmonic grid not only optimizes energy utilization

but also unlocks opportunities for light propagation in a host of optoelectronic applications. The integration of diverse plasmonic models, encompassing silver nanoparticles and plasmonic grids, holds immense promise for advancing the efficiency and functionality of thin-film solar cells. These innovative strategies not only augment sunlight absorption but also minimize reflective losses, thus paving the way for more sustainable and efficient solar energy solutions. As we delve deeper into the intricacies of plasmonics and their applications, the potential for transformative breakthroughs in renewable energy technology continues to expand, offering hope for a cleaner and more sustainable energy future [17-19].

In recent years, research endeavors have shed light on the profound influence of temperature fluctuations on the performance of solar cells. The findings from these investigations underscore a pivotal relationship between temperature and solar cell efficiency, revealing a notable decrease in efficiency as temperatures rise. This phenomenon can be primarily attributed to the intricate recombination processes occurring within the solar cell. Central to our understanding of this interplay are key electrical properties, namely the short-circuit current density ( $J_{sc}$ ) and the open-circuit voltage ( $V_{oc}$ ), which play a crucial role in the assessment and optimization of solar cell efficiency [20–23].

The research conducted in this domain has unraveled a significant trend wherein solar cell efficiency experiences a marked decline as temperatures increase. This decline can be ascribed to the heightened propensity for electron-hole recombination at elevated temperatures. As the thermal energy in the system rises, electrons and holes are more likely to recombine, leading to a decrease in the number of charge carriers available for electricity generation. Understanding and mitigating this temperature-induced efficiency loss is paramount in the pursuit of more robust and reliable solar cell technologies. To comprehensively assess and address the impact of temperature on solar cell performance, it is imperative to scrutinize key electrical properties,  $J_{sc}$  and  $V_{oc}$ . Short-circuit current density ( $J_{sc}$ ) represents the maximum current that a solar cell can generate under specific illumination conditions, while open-circuit voltage ( $V_{oc}$ ) signifies the voltage when no current flows through the cell. Together, these properties offer valuable insights into the efficiency ( $\eta$ ) of the solar cell [23-24].

The short-circuit current density ( $J_{sc}$ ) reflects the ability of the solar cell to generate current under given environmental conditions, including temperature. Variations in  $J_{sc}$  under different temperature scenarios provide crucial data for optimizing solar cell designs to minimize temperature-related efficiency losses. Similarly, open-circuit voltage ( $V_{oc}$ ) is a critical parameter that offers insights into the potential difference across the cell's terminals. Understanding how  $V_{oc}$  is affected by temperature fluctuations is essential for devising strategies to maintain cell efficiency under varying thermal conditions. Recent research has illuminated the intricate relationship between temperature variations and solar cell performance, highlighting the propensity for efficiency declines due to enhanced recombination processes. The electrical properties,

particularly short-circuit current density ( $J_{sc}$ ) and open-circuit voltage ( $V_{oc}$ ), serve as fundamental metrics in assessing and mitigating these efficiency losses. As we delve deeper into this domain, we anticipate that the insights gained will contribute to the development of more resilient and efficient solar cell technologies capable of withstanding the challenges posed by temperature variations, thus accelerating our transition to sustainable and renewable energy sources [24-27].

This study delves into the intricate relationship between temperature variations and the efficiency of Surface Plasmon Polariton (SPP) thin-film solar cells. Leveraging advanced 3D numerical simulations, we aim to comprehensively model and analyze the behavior of SPPs within the context of solar cell performance. These simulations employ a plasmonic grid arrangement, strategically positioned either at the back electrode or the back wiring of the solar cell. Our investigation explores how temperature-induced changes affect the optical behavior and energy absorption mechanisms within the solar cell. Two key phenomena are central to our analysis: the refraction of light at the grating surface, extending the path length of reflected light, and the excitation of surface plasmons within the troughs. These mechanisms, coupled with the plasmon resonance effect, collectively contribute to enhancing the absorption of the absorber layer, thereby amplifying the overall efficiency of the solar cell.

The study elucidates the pivotal role played by the grating surface in refracting incident light, resulting in a more extended path for reflected photons. This extended path length increases the likelihood of light absorption within the solar cell, thereby elevating its efficiency. Simultaneously, our investigation addresses the excitation of surface plasmons within the troughs of the plasmonic grid. These excited plasmons are intricately linked to the absorption process, further enhancing the solar cell's ability to harness incident light for energy conversion.

In conjunction with the effects of refraction and surface plasmon excitation, our study underscores the importance of implementing sound lighting techniques to maximize solar cell efficiency. The amalgamation of these techniques, along with the plasmon resonance effect, creates an environment conducive to heightened light absorption within the absorber layer of the solar cell. Consequently, this optimization manifests in improved solar cell parameters, including short-circuit current, open-circuit voltage, and high-temperature efficiency.

In the scope of this investigation, our analytical framework encompasses semiconductor models, specifically incorporating drift-diffusion models and electrostatic modules. Additionally, electronic devices have been meticulously employed to scrutinize the intricate behaviors pertinent to our study. Within the ambit of temperature manipulation, our investigation spans a range from 300 K to 360 K, aimed at comprehensively assessing the impact of thermal variances on the operational efficacy of solar cells.

The central objective of this scholarly exposition is threefold. First and foremost, we endeavor to construct intricate models elucidating the geometric intricacies of triangular Surface Plasmon Polaritons (SPPs). Secondly, our research extends to probing the intricate nexus between

temperature disparities and the overall efficiency of solar panels, dissecting the nuanced interplay between thermal conditions and photovoltaic performance. Lastly, we aspire to derive a harmonious equilibrium between these geometric structures and their thermal environment, thereby shedding light on the delicate balance that governs their functionality.

The subsequent sections of this manuscript are arranged in the following manner for systematic exploration of our research findings. Section 2 delves into an in-depth exploration of the architecture and constituent elements characterizing solar cells. Moving on to Section 3, a comprehensive exposition is provided regarding the intricacies of the model harnessed for this investigative endeavor. In Section 4, an extensive scrutiny of the obtained results ensues, with a meticulous examination of potential outcomes and associated implications. Finally, the culminating insights are distilled into an analytical conclusion, which can be found in Section 5.

## **2. The Model Structure and Parameters**

Illustrated in Figure 1 is the intricate composition of the solar cell, which comprises four distinct layers, each playing a crucial role in its operation. These layers are meticulously detailed as follows:

1. An uppermost SiO<sub>2</sub> shielding layer, serving as the initial protective barrier.
2. A Si absorber layer, featuring a PIN pattern, strategically designed for efficient photon absorption and charge separation.
3. An additional SiO<sub>2</sub> layer, further contributing to the structural integrity and performance enhancement of the solar cell.
4. The entirety of the upper section of the rear reflector, which is pivotal in redirecting incident light for increased absorption.

It is worth noting that the presence of a gold layer is integral to the grating process, which plays a pivotal role in the solar cell's operation. As discernible in Figure 1, the Surface Plasmon Polaritons (SPPs) exhibit dimensions of 10 x 10 nm, while the horizontal spacing between the SPP gold layer elements is maintained at 30 nm, a critical parameter influencing their behavior and interaction with incident light.

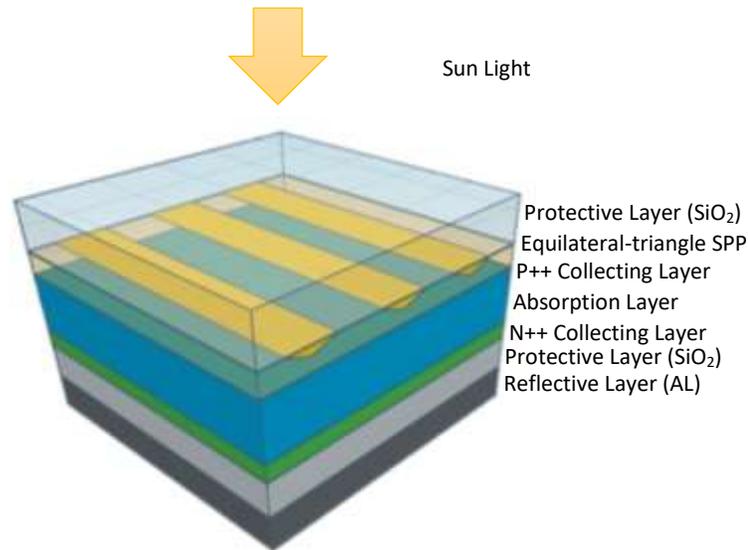


Figure 1. Structure of an equilateral triangle SPP PIN device.

In Table 1, you will find a comprehensive compilation of the parameters meticulously employed throughout the course of this research endeavor. Additionally, Figure 2 provides a visual representation of the doping profile intrinsic to the PIN layer under scrutiny within this study. Within this PIN layer, the doping concentration of the N++ layer stands at a robust  $1 \times 10^{19}$  atoms/cm<sup>3</sup>, gradually diminishing to  $1 \times 10^{18}$  atoms/cm<sup>3</sup> in correspondence with its layer thickness. It is essential to note that, due to the inherent limitations of certain fabrication processes, doping may not be consistently generated across the entire layer. Consequently, a thin layer, measuring 20 nm and featuring a doping concentration of  $1 \times 10^{18}$  atoms/cm<sup>3</sup>, is deliberately formed. This approach is equally applied to the P++ layer for consistency and comparability.

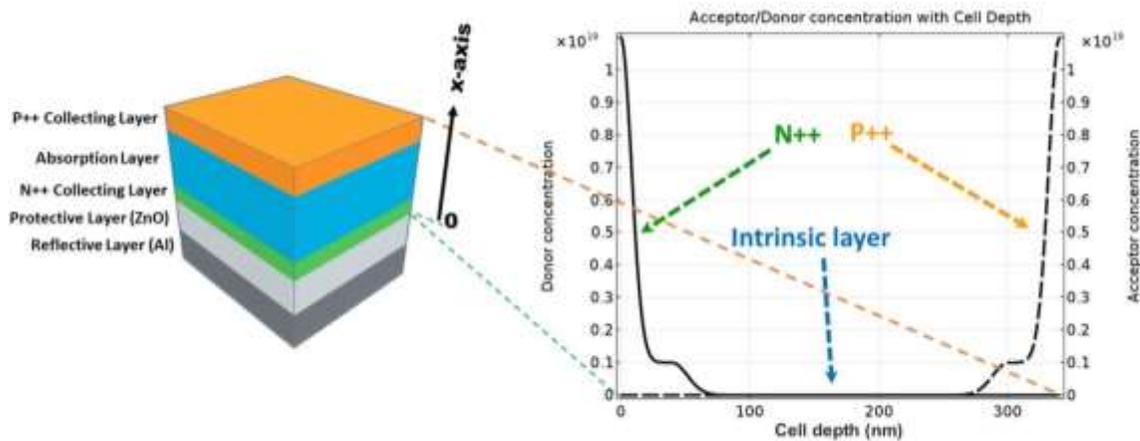


Figure 2. The doping profile used in the simulation of the PIN device model [18].

Table. 1 The value given for each parameter in thin-film solar cells [19].

Parameter name	Value
Anode doping concentration (P <sup>++</sup> -doping)	$1 \times 10^{19}$ (atom /cm <sup>3</sup> )
Cathode doping concentration (N <sup>++</sup> -doping)	$1 \times 10^{19}$ (atom /cm <sup>3</sup> )
a-Si, intrinsic carrier concentration	$1.5 \times 10^{15}$ (atom /cm <sup>3</sup> )
Thickness (I, Si)	260 nm
Thickness (N <sup>++</sup> , Si)	40 nm
Thickness (P <sup>++</sup> , Si)	40 nm
Thickness (SiO <sub>2</sub> )	75 nm
angle of incidence	[0°]
a-Si, electron mobility	1500 (cm <sup>2</sup> / (V.s))
a-Si, hole mobility	450 (cm <sup>2</sup> / (V.s))
Si, band gap @300 K	1.74 [eV]
Si, electron affinity	4.00 [eV]
a-Si intrinsic, electron carrier lifetime	20 ns
a-Si intrinsic, hole carrier lifetime	20 ns
a-Si N <sup>+</sup> , electron carrier lifetime	0.0001 ns
a-Si N <sup>+</sup> , hole carrier lifetime	10 ns
a-Si P <sup>+</sup> , electron carrier lifetime	10 ns
a-Si P <sup>+</sup> , hole carrier lifetime	0.0001 ns
Back reflector (silver)	500 nm
Input power flow (P <sub>in</sub> )	100 mW/cm <sup>2</sup>
Si, bandgap at 300 K	1.74 eV
Si, relative permittivity	11.7

An inner layer, boasting a thickness of 260 nm, is strategically interposed between these two doped layers. This design, as previously documented in references [28] and [29], serves as a critical structural element within the PIN layer configuration, influencing its electronic properties and operational performance.

### 3. The mathematical model of the SPPs

#### 3.1 The excitation of the SPPs

In a manner akin to the excitation of photons and electrons, Surface Plasmon Polaritons (SPPs) can also undergo excitation. This process involves the interaction between SPPs and incident photons sharing identical frequencies and energies. It's worth noting that due to this frequency correspondence, the energy possessed by free photons at this specific frequency surpasses that of the SPPs. Consequently, there exists a temporal discrepancy allowing free-space photons to directly couple with SPPs as they traverse the atmosphere. However, it's crucial to distinguish that, unlike free-space photons interacting with smooth metallic surfaces, SPPs lack the ability to instigate energy generation within dielectric materials [30].

Expanding further on this concept, the excitation of SPPs presents a fascinating phenomenon in the field of plasmonics. These surface waves, formed at the interface between a metal and a

dielectric material, exhibit unique properties and behaviors when subjected to incident photons. Much like photons themselves, SPPs require precise resonance conditions to be excited effectively. For optimal excitation, incoming photons must share the same frequency and energy as the SPPs they encounter. This resonance condition ensures efficient energy transfer between the two entities. However, it's important to emphasize that there is an inherent energy mismatch between SPPs and free-space photons due to the specific frequency requirements for SPP excitation. This energy disparity implies that free photons arriving from the atmosphere possess greater energy at the resonant frequency compared to the SPPs propagating on the metal-dielectric interface. Consequently, free-space photons can readily couple with SPPs, creating opportunities for intriguing applications in nanophotonics and plasmonic devices.

Notably, the temporal aspect of this interaction is a critical factor. The delay caused by the frequency mismatch allows free photons to bridge the gap between the atmosphere and the SPPs, enabling efficient energy transfer and potentially leading to various practical applications in sensing, imaging, and communication systems.

However, it's essential to highlight a limitation of SPPs: their inability to generate energy within dielectric materials. While SPPs exhibit remarkable properties on metal surfaces, their energy transfer capabilities are limited to metals and their immediate vicinity. This distinction underscores the importance of tailoring plasmonic systems to specific material contexts and desired applications. Further exploration of these phenomena and their practical implications remains an exciting frontier in the field of plasmonics.

### 3.2 The fields and dispersion relation in SPP

The characteristics and behavior of Surface Plasmon Polaritons (SPPs) can be elucidated through the application of Maxwell's equations, which govern the electromagnetic phenomena. Specifically, in the vicinity of the metal-dielectric interface, we encounter distinct electromagnetic impedance values. At this interface, the impedance, denoted as  $Z$ , assumes a value of 0, signifying the point of transition between the metal and dielectric regions. As one moves deeper into the metal, the impedance becomes negative ( $Z < 0$ ), reflecting the properties of metallic materials. Conversely, within the dielectric medium, the impedance takes on a positive value ( $Z > 0$ ), in accordance with the characteristics of dielectric materials.

In a more formal representation, considering the spatial coordinates ( $x, y, z$ ) and the temporal dimension, we can express the electric and magnetic fields associated with SPPs as described by the relevant literature [16, 31].

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

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

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

where  $n$  denotes the physical properties (1 for  $z < 0$  for metals, 2 for  $z > 0$  for dielectrics).

The angular frequency of a wave, denoted as  $\pm\omega$ , carries distinct sign conventions depending on the material medium it propagates through. For metals, a positive sign ( $+\omega$ ) is employed, while for dielectrics, a negative sign ( $-\omega$ ) is utilized. This sign distinction reflects the inherent characteristics and behavior of electromagnetic waves within these different types of materials. Within the context of Surface Plasmon Polaritons (SPPs), the electric field vector components, specifically  $E_x$  and  $E_z$ , exhibit significant behavior. These components are intertwined with the magnetic field component  $H_y$ , particularly the  $y$ -component of the magnetic field. All other components of the electric and magnetic fields ( $E_x$ ,  $E_z$ , and  $H_y$ ) are rendered negligible and effectively equal to zero in the context of SPPs.

It's important to recognize that SPPs can be classified as transverse magnetic (TM) waves, indicating that the magnetic field vector and wave propagation direction are orthogonal. The wave vector, symbolized as  $K$ , characterizes the direction and magnitude of the wave propagation for SPPs. In scenarios where SPPs are absent, the wave exhibits a mixed character, characterized by a combination of real and imaginary components. Specifically, the wave oscillates in the  $x$ -direction while changing exponentially in the  $z$ -direction. This behavior is indicative of how electromagnetic waves interact with dielectric and metallic interfaces.

In cases where the wave vector components in the  $z$ -direction ( $k_z$ ) exhibit variation, particularly  $k_{z,1}$  being distinct from  $k_{z,2}$ , the wave vector component in the  $x$ -direction ( $k_x$ ) remains the same. This property underscores the unique behavior of SPPs, where they propagate primarily parallel to the metal-dielectric interface and are highly sensitive to the properties of the materials involved.

$$\frac{H_0}{E_0} = -\frac{\epsilon_1 \omega}{k_{z,1} C} \quad \text{or} \quad \frac{H_0}{E_0} = -\frac{\epsilon_2 \omega}{k_{z,2} C}, \quad \text{where } \epsilon_1 \text{ is the permittivity of the metal.}$$

The wall geometry of Surface Plasmon Polaritons (SPPs) plays a pivotal role in manipulating both the magnitude and direction of the electric and magnetic fields. By tailoring the geometry of the SPP structure, we have the capability to influence and adjust the values of  $E_0$  (the magnitude of the electric field) and  $H_0$  (the magnitude of the magnetic field) to accommodate the specific shape and characteristics of the SPP structure, which may deviate from a traditional grid-like configuration.

In the equation presented below, waves characterized by this specific structure demonstrate the unique capability to satisfy Maxwell's equations in a single configuration. This emphasizes the versatile nature of SPPs and their potential to serve as a platform for engineering and controlling electromagnetic fields, making them valuable in various applications, including nanophotonics, plasmonic devices, and metamaterials.

$$\frac{k_{z,1}}{\varepsilon_1} + \frac{k_{z,2}}{\varepsilon_2} = 0 \quad (4)$$

and

$$k_x^2 + k_{zn}^2 = \varepsilon_n \left(\frac{\omega}{c}\right)^2 \quad \text{for } n = 1, 2 \quad (5)$$

Solve equations (4) and (5) to get the difference between waves propagating on the surface:

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

The metal-dielectric model is derived from the free electron model, which accounts for the flow of electrons and is instrumental in mitigating damping effects [32].

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2} \quad (7)$$

where the plasma frequency can be written in SI units as:

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

where  $n_e$  is the electron density,  $e$  is the electron charge,  $m^*$  is the electron's effective mass, and  $\varepsilon_0$  is the free-space permittivity.

Surface Plasmon Polaritons (SPPs) exhibit intriguing behavior that resembles that of photons, particularly when their wave vector, denoted as "K," is at low values. However, as the strength of the interaction between these SPPs and the material interface intensifies, a fascinating transformation occurs. The SPPs start to deviate from their photon-like behavior, exhibiting a bending phenomenon as they approach a critical point known as the "surface plasmon frequency." At this critical threshold, the SPPs undergo a remarkable transition, acquiring distinct characteristics that set them apart from traditional electromagnetic waves.

In a manner akin to their metallic counterparts, these SPPs can be effectively analyzed within the context of metal-dielectric multilayer configurations. It is reasonable to assume that the primary driving forces behind SPP behavior lie in the intricate interplay of electromagnetic fields and electric charge transfer dynamics within these composite structures [33]. This wave, perched at the boundary of metamaterials, represents a captivating frontier in the realm of plasmonics. It gracefully propagates along the interface, showcasing its unique properties and offering a wealth of opportunities for innovative applications in fields ranging from nanophotonics to advanced materials science.

In essence, Surface Plasmon Polaritons emerge as captivating entities within the electromagnetic spectrum, displaying dualistic behavior akin to both photons and traditional surface waves. Their evolution from photon-like behavior to the enigmatic realm of surface

plasmon frequencies, and their close association with complex material interfaces, makes them a subject of great interest and exploration in the realm of modern physics and engineering. Electromagnetic fields typically exhibit a characteristic behavior near material boundaries, wherein their intensity diminishes exponentially as they approach the boundary. Within the confines of a solid block, these fields generally do not propagate extensively. This phenomenon is illustrated in Figure 3. In the context of plasmonic structures, the thickness of the substrate plays a critical role and depends on the desired portion of permeability within the film. The precise positioning of this substrate is determined by the width of the dielectric layer, as demonstrated in Figure 3.

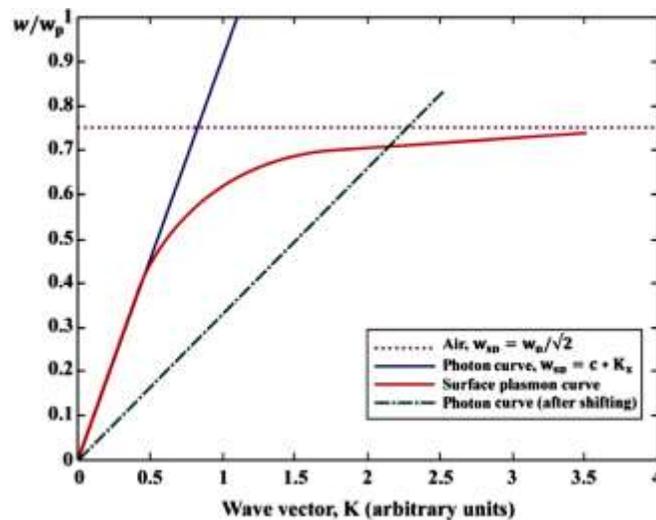


Figure 3: The dispersion phenomenon encountered as a photon interacts with a surface plasmon. As the wave vector "K" increases, a notable transformation occurs in the distribution curve. It gradually bends and eventually approaches an asymptotic limit [34].

The figure also highlights an intriguing effect when a thin dielectric layer is affixed to a metal thin film layer. This interaction alters the dispersion relationship of the electromagnetic waves, leading to changes in the propagation angle. Notably, the oscillation of the resonance angle is directly proportional to the optical thickness, a parameter contingent on the disparity between the refractive index and the depth of the film. This relationship underscores the intricate interplay between material properties and wave behavior in plasmonic systems, rendering them a fertile ground for research and innovation in fields like nanophotonics and metamaterial engineering.

### 3.1 The propagation length and the skin depth in the SPP

The SPP will stretch the top longitudinally, as absorption causes energy to be transferred to the metal. The surface plasmon concentration decreases with the square of the electric field, so at

distance  $x$  the density decreases by a factor of  $\exp\{-2k_x''\}$ . The propagation length can be expressed as the length corresponding to the  $1/e$  decrease of the SPP power.

Surface Plasmon Polaritons (SPPs) exhibit a fascinating characteristic where they elongate predominantly in the longitudinal direction as they absorb energy, transferring it to the metal surface. This longitudinal stretching effect is a consequence of the absorption process within the metal.

Moreover, the concentration of surface plasmons diminishes in relation to the square of the electric field strength. At a specific distance " $x$ " along the propagation path, the density of these surface plasmons diminishes significantly, scaling down by a factor determined by the exponential term  $\exp\{-2k_x''\}$ . To quantify the extent of SPP propagation, we can define the propagation length as the distance over which the SPP power decreases to  $(1/e)$  of its initial value. This metric provides a practical measure of how far SPPs can travel while maintaining their significant power and concentration.

This condition is satisfied when the length is [34]:

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

Likewise, the electric field exhibits a gradual decrease and takes on a corner-like shape as it interfaces with the metal surface. To assess the depth of Surface Plasmon Polariton (SPP) diffusion within metals, it is common practice to employ a low-temperature shell structure model. This model helps estimate the penetration depth of SPPs into the metal, offering valuable insights into how far these plasmonic waves can extend within the metallic medium. Once the SPP diffusion depth has been determined, it is pertinent to consider the behavior of the electric field as it transitions into the adjacent dielectric medium. Beyond the calculated diffusion depth, the electric field in the dielectric begins to taper off gradually. This transition from the metal to the dielectric is a crucial aspect of understanding the interaction of SPPs with materials of different properties.

The quantification and interpretation of this reduction in field intensity within both the metal and dielectric media provide essential information for characterizing the behavior of SPPs at material interfaces. These insights are fundamental to the design and optimization of plasmonic devices and structures, offering opportunities for innovative applications in fields such as nanophotonics and optical sensing [35].

$$Z_i = \frac{\lambda}{2\pi} \left( \frac{|\varepsilon_1 + \varepsilon_2|}{\varepsilon_i^2} \right) \quad (10)$$

Here, the symbol " $i$ " designates the medium through which propagation occurs. Surface Plasmon Polaritons (SPPs) exhibit a high degree of sensitivity to subtle variations in skin depth. This unique characteristic endows them with the capability to effectively discern and detect surface

irregularities or inhomogeneities. This sensitivity to small-scale variations makes SPPs a powerful tool for applications involving surface analysis and characterization.

### 3.2 The five-parameter (single-diode) model

Figure 4, Illustrated here, is a schematic representation of a typical diode, comprising four fundamental components:

1. **Photovoltaic Current Source (I<sub>ph</sub>):** This component represents the photovoltaic or photo-generated current source, which results from the conversion of incident light into electricity within the diode. It embodies the photovoltaic effect, where photons striking the diode's active material generate electron-hole pairs, thereby inducing a photocurrent.
2. **Diode:** The diode itself is a core component responsible for facilitating the flow of electric current in one direction while significantly impeding it in the opposite direction. It is characterized by its characteristic voltage-current relationship, typically described by the Shockley diode equation.
3. **Ideal Electron-Hole Recombination Current:** According to the principles of Shockley diffusion theory, an ideal electron-hole recombination current arises from the diffusion and recombination of charge carriers within the diode. This current represents a key aspect of the diode's behavior under various operating conditions.
4. **R<sub>se</sub> and R<sub>sh</sub>:** The parameters R<sub>se</sub> and R<sub>sh</sub> encompass all sources of losses and resistive elements in the diode circuit. R<sub>se</sub> typically accounts for series resistance, which arises due to the intrinsic resistance of materials and connections within the diode. In contrast, R<sub>sh</sub> represents the shunt resistance, which is associated with parallel paths for current flow that can bypass the diode.

Studying the characteristics of these four main components is vital for analyzing and designing diode-based devices.

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

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

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

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

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

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

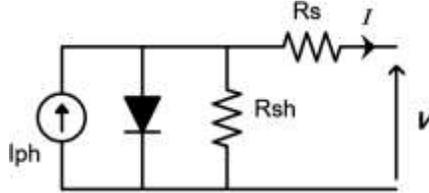


Figure 4. The equivalent circuit of the solar cell [36].

In the context of a diode, the term " $n_i$ " represents an ideally known constant. This constant signifies that the diode exhibits characteristics that deviate from Shockley's law of diffusion. In other words, it acknowledges that the diode's behavior may not perfectly adhere to the ideal behavior described by Shockley's model. Furthermore, " $I_m$ " and " $V_m$ " correspond to the current (I) and voltage (V) values associated with the maximum power point (MPP) of the diode. The MPP represents the operating conditions at which the diode generates the highest amount of electrical power output.

Additionally, " $V_{oc}$ " stands for the open-circuit voltage, which is the voltage across the diode when no current flows through it. " $I_{sc}$ " represents the short-circuit current, denoting the maximum current that the diode can provide when its voltage is forcibly reduced to zero. Lastly, " $V_t$ " denotes the thermal voltage, a parameter related to temperature and intrinsic material properties. Thermal voltage is a fundamental quantity in semiconductor physics and is associated with the energy distribution of charge carriers in a semiconductor.

These parameters and constants are essential in the analysis and characterization of diodes and are critical for determining their performance and efficiency in various electronic and photonic applications [36].

This simulation model provides a means to deduce the primary electrical parameters of solar cells, including key characteristics like open-circuit voltage ( $V_{oc}$ ) and short-circuit current ( $I_{sc}$ ) [37]. By employing this model, researchers and engineers can effectively analyze and predict the performance of solar cells under different conditions and configurations. This, in turn, aids in optimizing the design and efficiency of solar energy systems and contributes to advancements in renewable energy technology.

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

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

where FF is the fill factor that can be obtained from the J-V characteristic of the device.

#### 4. The simulation results for the PIN device

In this research endeavor, we have harnessed the capabilities of COMSOL Multiphysics 3D numerical simulations to delve into the behavior of photovoltaic (PV) systems. Specifically, we've adopted a comprehensive approach that integrates both electromagnetic and semiconductor models [38]. This amalgamation allows us to thoroughly assess the electrostatic and optical aspects of photovoltaic behavior. The structure of our thin-film solar cell simulation model, implemented using COMSOL Multiphysics, is structured as follows:

1. **Defining the Overall Electrical/ Optical Structure and Properties:** We commence by establishing a comprehensive framework that outlines the electrical and optical characteristics of our simulation. This step serves as the foundation for our subsequent analyses.
2. **Creation of 3D Models of Thin-Film Photovoltaic Cells:** We construct intricate 3D models of thin-film photovoltaic cells, taking into account the physical and geometrical intricacies of these structures. These models provide the spatial context for our simulations.
3. **Defining the Electromagnetic and Semiconductor Standards:** Next, we establish the governing standards and equations that describe the electromagnetic and semiconductor behaviors within our simulation. This entails specifying the physical laws and mathematical expressions that underpin the interaction of light and charge carriers in our PV system.
4. **Choosing the Appropriate Lattice Shape to Solve the Equation and Check the Solution:** We carefully select the lattice shape that aligns with our problem and chosen computational methods. This choice plays a pivotal role in ensuring the accuracy and reliability of our solutions.
5. **Identifying the Electromagnetic Semiconductor Output:** Finally, we analyze and interpret the output generated by our simulation, focusing on electromagnetic and semiconductor aspects. This step allows us to draw valuable insights and conclusions regarding the photovoltaic behavior of our thin-film solar cell.

By following this systematic approach, we aim to gain a comprehensive understanding of the intricate interplay between electromagnetic and semiconductor phenomena within thin-film photovoltaic systems. This, in turn, contributes to advancements in solar cell technology and our ability to harness solar energy efficiently.

In this study, the influence of temperature variation has systematically been investigated, ranging from 300 K to 360 K, on the electrostatic behavior of photovoltaic (PV) systems. This

examination serves to elucidate the response of the PV crystal to temperature fluctuations. Figure 5 illustrates the behavior of a thin-film PIN solar cell featuring a triangular Surface Plasmon Polariton (SPP) structure at different temperature levels. Our findings reveal a noteworthy trend: as temperature rises, the efficiency of the thin-film solar cell experiences a discernible decline. Specifically, we observed efficiencies of 14.92%, 14.34%, 14.07%, 14.18%, 13.90%, 13.72%, and 13.48% at temperatures of 300 K, 310 K, 320 K, 330 K, 340 K, 350 K, and 360 K, respectively. Notably, the triangular SPP configuration achieved its highest performance at 300 K.

The inclusion of a reflective substrate positioned behind the thin-film solar cell plays a critical role in enhancing overall efficiency. This reflector serves to redirect and scatter light that was not initially absorbed upon passing through the film. The specific shape and size of the SPP structure are tailored to the unique characteristics of the solar spectrum, which in turn dictates the amount of power the cell is capable of generating. By introducing the rear reflective substrate into the configuration, previously unabsorbed photons are guided back towards the PIN junction, optimizing light coupling and bolstering solar efficiency. Overall, our study underscores the significance of considering temperature effects in the design and optimization of thin-film solar cells, highlighting the potential for improvements in energy conversion efficiency through strategic structural modifications and reflective enhancements.

Certainly, temperature fluctuations have a significant impact on the behavior of semiconductor devices, including solar cells. One crucial effect of temperature variation is the alteration of the semiconductor's band gap. When the temperature increases, the band gap of the semiconductor tends to decrease. This reduction in the band gap is linked to an increase in the energy of electrons within the semiconductor. Essentially, as the temperature rises, electrons gain more energy. This elevated energy level makes it easier for them to break free from their bonded positions within the semiconductor material. Consequently, the energy required to disrupt these bonds becomes lower, and this phenomenon leads to a reduction in the band gap.

In practical terms, as the temperature of a semiconductor-based device like a solar cell increases, the distinction between the energy levels of electrons in the valence band and the conduction band narrows. This narrowing of the energy band gap results in the generation of more conduction electrons, which are free to carry electrical current.

This effect is particularly significant in photovoltaic applications, where the interaction of photons with the semiconductor material relies on the energy level difference between incident photons and the semiconductor's band gap energy. In summary, the energy behavior of semiconductor materials with respect to temperature is a fundamental aspect that affects the performance of solar cells and other semiconductor devices. Understanding how temperature variations influence the band gap and carrier generation is crucial for optimizing the efficiency and reliability of these devices [39, 41].

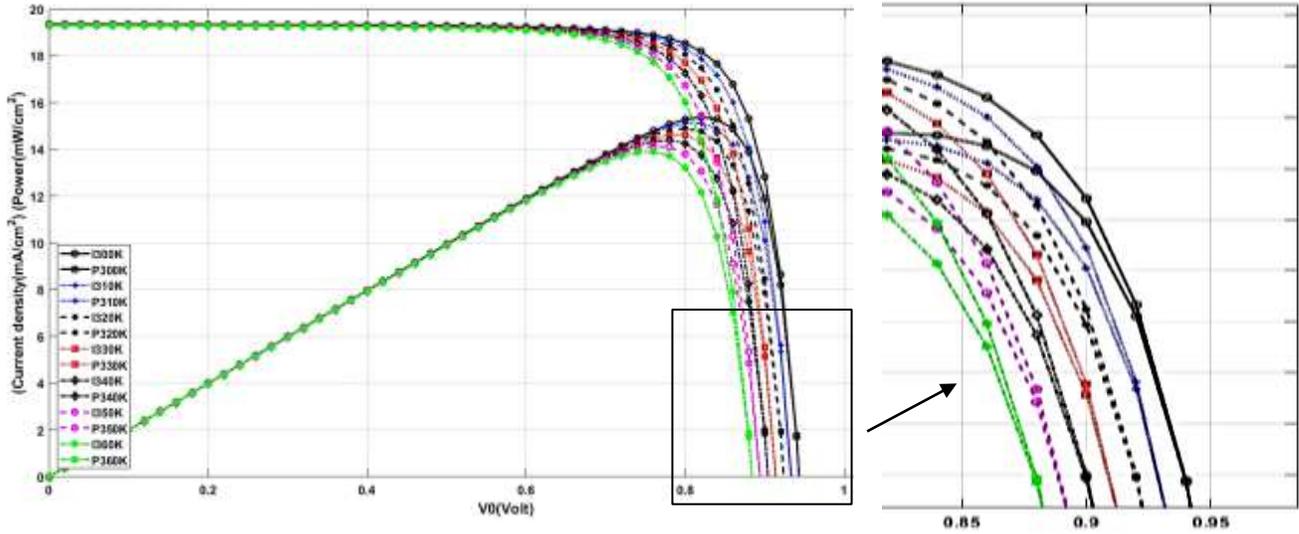


Figure 5. Temperature dependence characteristics of  $J$ - $V$  and  $P$ - $V$  curves of the triangular SPP thin film Solar cell.

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{(T + \beta)} \quad (19)$$

where  $E_g(T)$  represents the band gap energy difference  $T$ , and  $E_g(0)$  is the band gap of the semiconductor, and  $\alpha$  and  $\beta$  are two constants. The short-circuit current rate ( $J_{sc}$ ) depends on the solar spectral radiation and the first photon flux ( $N_{ph}$ ) and is defined as follows:

The relationship between the band gap energy difference,  $E_g(T)$ , at temperature  $T$  and the band gap of the semiconductor at absolute zero temperature,  $E_g(0)$ , can be expressed mathematically using the following equation:

$$E_g(T) = E_g(0) - \alpha \cdot T^2 / (T + \beta),$$

where:

- $E_g(T)$  represents the band gap energy at temperature  $T$ .
- $E_g(0)$  is the band gap of the semiconductor at absolute zero temperature.
- $\alpha$  and  $\beta$  are two constants that influence the temperature dependence of the band gap.

Additionally, the short-circuit current rate,  $J_{sc}$ , which is a critical parameter in solar cell performance, relies on factors such as the spectral radiation of incident sunlight and the first photon flux,  $N_{ph}$ . This rate can be defined as follows:

$$J_{sc} = q \int_{h\nu=E_g}^{\infty} \frac{dN_{ph}}{dh\nu} dh\nu \quad (20)$$

This equation essentially integrates the contribution of photons across the entire solar spectrum, taking into account the energy of individual photons (determined by their wavelength) and converting it into an electric current, which is an essential parameter in evaluating the performance of a solar cell. Open-circuit voltage decreases when temperature rises. This is due to reverse saturation current resulting from an increase in the  $n_i$  material concentration and a decrease in the band gap of the semiconductor material. In addition, the increase in the temperature of the cell affects its electrical properties and reduces the efficiency of the solar cell.

Furthermore, the data presented in Table 2 underscores the crucial role of temperature regulation in shaping the efficiency and electrical characteristics of photovoltaic systems. By meticulously analyzing the simulation results, we gain valuable insights into the interplay between temperature and PV performance.

The findings in Table 2 highlight that the equilateral-triangle SPP-based configuration, when operated at 300 K, emerges as the most favorable choice in terms of electrical parameters. This configuration yields optimal values for these parameters indicating superior photovoltaic efficiency under these conditions. These results are particularly significant for practitioners and researchers in the field, as they provide a clear direction for designing and optimizing photovoltaic systems.

Additionally, it is worth noting that the observed improvement in efficiency and  $R_s$  values as temperature is controlled reaffirms the importance of temperature management in photovoltaic applications. This insight can guide the development of more effective thermal control strategies for photovoltaic installations, ultimately leading to increased energy harvesting and system reliability. This comprehensive analysis presented in Table 2 not only underscores the significance of temperature control in photovoltaic systems but also provides valuable guidance for optimizing their electrical parameters and efficiency. This research contributes to our understanding of how temperature influences photovoltaic performance, paving the way for more efficient and reliable solar energy solutions.

The open-circuit voltage ( $V_{oc}$ ) of a solar cell is a critical parameter that represents the voltage at which the solar cell operates when there is no external load connected to it. It essentially corresponds to the maximum voltage potential generated by the solar panel when the internal photogenerated current is not being drawn. In other words, it's the voltage that the solar circuit achieves in the absence of any electrical load. However, it's important to note that the efficiency

of a solar cell is not solely determined by its open-circuit voltage. It is also influenced by various factors, including the amount and intensity of incident sunlight and the temperature at which the solar cell operates. These external conditions can significantly impact the overall performance and efficiency of the solar cell.

Table. 2 Photovoltaic parameters at different temperatures with an input power of 100 mW/cm<sup>2</sup>.

	<b>300</b>	<b>310</b>	<b>320</b>	<b>330</b>	<b>340</b>	<b>350</b>	<b>360</b>
<b>J<sub>sc</sub> (mA/cm<sup>2</sup>)</b>	<b>19.35</b>	19.34	19.33	19.32	19.31	19.31	19.3
<b>P<sub>max</sub> (mw)</b>	<b>15.38</b>	15.11	14.89	14.63	14.4	14.15	13.87
<b>V<sub>oc</sub> (v)</b>	<b>0.945</b>	0.937	0.926	0.918	0.907	0.898	0.887
<b>J<sub>m</sub> (mA/cm<sup>2</sup>)</b>	<b>18.19</b>	17.88	18.05	18.19	17.9	18.06	17.74
<b>V<sub>m</sub> (v)</b>	<b>0.82</b>	0.81	0.8	0.78	0.78	0.76	0.76
<b>R<sub>s</sub> (Ω)</b>	<b>0.686</b>	0.766	0.8	0.758	0.709	0.764	0.715
<b>R<sub>sh</sub> (Ω)</b>	<b>711</b>	547	609	690	553	608	487
<b>FF</b>	<b>0.81</b>	0.8	0.78	0.8	0.79	0.79	0.78
<b>η (%)</b>	<b>14.92</b>	14.34	14.07	14.18	13.9	13.72	13.48

To evaluate and compare the performance of different solar cell systems, it is common practice to consider not only their open-circuit voltage but also their overall efficiency under specific environmental conditions. By comparing the outputs of various systems, researchers and engineers can gain valuable insights into the effectiveness of different solar cell technologies and their suitability for specific applications.

## 5. CONCLUSIONS

In this research study, we embarked on a comprehensive analysis and assessment of the electrical and optical characteristics of thin-film solar cells, focusing on a temperature range spanning from 300 K to 360 K. We conducted a meticulous examination of these properties, individually scrutinizing their electrical and optical aspects, employing advanced 3D numerical simulations facilitated by the versatile COMSOL Multiphysics software. Our investigation delved deeply into the optical behaviors of photon Surface Plasmon Polariton (SPP) solar cells, exploring phenomena such as light absorption and diffraction. This rigorous exploration of the optical

domain unveiled significant insights into the interaction of light with these specialized solar cell structures.

One of the prominent findings of our study was the temperature-dependent efficiency of thin-film solar cells. Specifically, as the temperature increased within the prescribed range, a notable decrease in solar cell efficiency was observed. Within this context, we achieved a remarkable efficiency of 14.92% for thin-film solar cells employing triangular SPP configurations. Notably, this achievement underscores the potential of tailored SPP structures in enhancing solar cell performance. Furthermore, our research emphasized the critical role of optimizing the series resistance and enhancing electronic parameters to boost solar energy conversion. These factors are instrumental in harnessing and augmenting the solar energy harvested by the cells, thereby contributing to the overarching goal of advancing renewable energy technologies. In summary, this study provides valuable insights into the intricate interplay of temperature, optical properties, and electrical performance in thin-film solar cells. It sheds light on strategies to optimize their efficiency and underscores the promise of innovative SPP structures in advancing solar energy conversion technologies.

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**Consent for publication** All authors are accepting to submit and publish the submitted work.

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