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A MATLAB-BASED USER INTERFACE TO STUDY THE MULTI-REFLECTIONS AND LIGHT ABSORPTION IN TEXTURED SOLAR CELL SURFACES

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ABSTRACT

Improving the efficiency of solar cells is important as it is a sustainable way of energy production with a relatively low power conversion efficiency (PCE). To enhance the efficiency of solar cells, textures can be introduced on the surface which can minimize light ray reflectance, leading to increased light absorption and improvement in overall efficiency. Introduction of texture can also improve the hydrophobicity of the surface which can enhance the self-cleaning capability of solar panels. In this study, a MATLAB-based user interface is developed to facilitate assessing the sunlight absorption in silicon-based solar cells having top layer as a microtextured surface. The user interface employs a multi-faceted mesh-grid algorithm to design 3D textural surface geometries. Core to the program's functionality is advanced ray tracing simulations that identify points of light intersection on these textures and determine the trajectory of light upon reflection. A notable feature of this user interface is its capability to simulate and analyze the complex phenomenon of multi-reflection in the structure. This iterative process allows for a comprehensive understanding of light interactions in textured surfaces, to find the best structure for maximum absorption. This user-interface provides clarity and ease of use in modeling and analyzing light absorption in textured solar cell surfaces. The modeling framework is validated using experimental observation, and the impact of six 3D surface textures on sunlight absorption of silicon solar cell is studied using the simulation framework. According to the simulation findings, the cavity texture provides more consistent light absorption compared to its protrusion counterpart. Furthermore, hemispherical cavities exhibit consistently high absorption across various incident angles. The results provide useful insights for improving light absorption in the solar cell.

Keywords: Solar cell, surface texture, light absorption, computer modeling.

1. INTRODUCTION

Life on earth is at risk from rapid climate change. Carbon dioxide emission from fossil fuels is a major contributor to climate change [1, 2]. As a result, alternative fuel sources are urgently needed to reduce fossil fuel dependence. A solar-powered alternative to fossil fuels may be an exciting development. The transformation of solar energy into electrical energy is generally carried out by photovoltaics, whereas conversion of solar power into heat is achieved by solar thermal system [3]. Research on solar cells has led to innovations in fabrication methods, making them more efficient and durable.

In solar cells, a significant challenge is the loss of efficiency due to light reflection, which prevents complete absorption of light, thereby reducing the overall conversion efficiency [4]. A featureless surface receives light that comes at different angles; portion of it is reflected and wasted, while others are transmitted or absorbed. Light trapping process uses these potentially wasted rays productively to enhance light absorption in solar cells to increase its efficiency [4]. This process can be done by different techniques such as surface texturing, anti-reflection coatings, and doping of materials [5].

The efficiency of solar cells can be improved by increasing the optical route of light inside the absorber material by using surface structures, such as surface patterns, or rough surfaces, periodic gratings that elongate the route of light. This can cause light trapping or scattering at periodic photonic crystal geometry [6, 7]. Koppel et al. [8] explored the enhancement of light absorption in crystalline silicon thin-film solar cells using nanoimprint-textured glass superstrates which enhance short-circuit current density by 5 percent compared to the planar device. He et al. [4] reported that using a pyramid-shaped micro-structured polydimethylsiloxane (MST-PDMS) anti-reflection film on organic solar cells notably increased light absorption and increased power conversion efficiency by 10.18%. Enhancing the light absorption within the silicon layers is a critical aspect of these methods [4, 8], achieved through specific texturing of solar cell's top surface. This texturing not only enlarges the available surface area for absorption but also minimizes the amount of light reflected away from the cell. The culmination of these effects is a marked increase in the efficiency of solar cells.

Despite all these advances, continuous research and development are essential to overcome existing limitations and achieve higher levels of efficiency. For example, introduction of uniform texture, especially with very small pyramids (e.g., 200 nm), can result in high reflection loss and lower efficiency [9, 10]. Advanced texturing techniques such as reactive ion etching are effective but costly and complex, while methods like colloidal lithography require precise control and expensive equipment, limiting their scalability [10]. Additionally, textured surfaces must maintain mechanical stability and integrity, with subwavelength structures potentially affecting durability [10]. Electrical properties can also suffer if texturing is not optimized, leading to increased resistance and reduced efficiency [9]. Scaling these processes for industrial use while maintaining quality remains a significant challenge [9, 10]. Finding the optimal surface texture geometry for maximizing light absorption is complex due to varying effectiveness of textures like pyramids, cones, and hemispheres under different conditions. This optimization involves balancing texture dimensions, material properties, and external factors such as wavelength and angle of incidence, necessitating extensive computational modeling and analysis. The interaction of light with textured surfaces involves multiple reflections, transmissions, and absorptions, which necessitates accurate modeling and experimental validation for providing guidelines for maximizing light absorption. Further investigation into the optimal surface texture of solar cells is particularly crucial in this endeavor.

This research aimed to develop a modeling framework that estimates sunlight absorption on silicon solar cells with textured surface, considering multiple reflection and absorption events. The goal is to enhance solar cell efficiency by identifying the optimal surface texture geometry to maximize sunlight absorption. To facilitate this, a MATLAB-based user interface is developed, which enables the evaluation of sunlight absorption based on various parameters including texture geometry, dimensions, material properties, wavelengths, and angles of incident light.

2. MODELING FRAMEWORK

In silicon-based devices, texturing is often used to reduce reflectivity and enhance light absorption, thereby improving efficiency. However, the effectiveness of texturing is highly dependent on the specific patterns and scales of the textures applied. Investigation into the interplay between surface texture, multi-reflection of incident sunlight, sunlight absorption due to multi-reflection, and photovoltaic efficiency presents pivotal insights for advancing solar cell technologies. Numerical simulation can be employed to study the relationships and find the surface texture that can maximize the overall light absorption and efficiency.

The incident angle of the light ray at the textured surface, which depends upon initial incident angle and the starting position of ray, is calculated based on the orientation of the surface at the point of interaction. This incident angle is very important, as it modulates the Fresnel equations [11] that govern the behavior of light at the interface of two media. These equations precisely quantify the partitioning of light into its reflected, transmitted and absorbed components, according to the relations [11]:

$$Reflectance\ (R) + Transmittance\ (T) = 1 \quad (1)$$

Where,

$$R = \left| \frac{n_1 \times cos(\theta i) - \left(\sqrt{n_2{}^2 - n_1{}^2 \times sin(\theta i)^2}\right)}{n_1 \times cos(\theta i) + \sqrt{n_2{}^2 - n_1{}^2 \times sin(\theta i)^2}} \right|^2 \quad (2)$$

$$T = exp(-\alpha \times d) \quad (3)$$

Where, n_1, n_2 are refractive index of two medium and θi is the incident angle of light ray with the surface normal, α is the absorption coefficient and d is the thickness of the material. Additionally, absorption of light within the silicon material follows Beer's Law [12], offering a detailed perspective on how surface texture affects light absorption, as described by the equation [12]:

$$I = I_0 \times e^{(-\alpha \times d)} \quad (4)$$

Where, I_0 is the initial intensity of light, α is the absorption coefficient ($\alpha = 4 \times \pi \times$k/wavelength), k is the extinction coefficient, d is the thickness of the material, and I is the intensity of transmitted light. Total absorption (A) is what remains of the light after reflection and transmission, which can be obtained from equation 1, 3, and 4 by using Kirchhoff's law [13].

$$A = 1 - R - T \quad (5)$$

The phenomenon of multi-reflection within textured surfaces plays a pivotal role in the enhancement of light absorption. As incident light interacts with a textured interface, it undergoes multiple reflections, effectively increasing the optical path length within the material. This increase in path length is not merely a linear extension but a complex, recursive interaction that keeps the light confined for longer periods, promoting higher probabilities of absorption. This intricate interplay of reflections within the micro-structured surface topology serves to improve the absorption capacity, enabling a more efficient conversion of light into other forms of energy.

2.1 Geometrical Setup and Surface Texturing

The geometrical setup of the simulation consists of a silicon substrate with various micro-textured surfaces. Each texture pattern is carefully modeled to represent real-world surface texturing used in silicon-based devices. The texture patterns include pyramidal structures, conical structures, and hemispherical structures, both protrusion and cavity, offering a broad spectrum of surface profiles for analysis (see Figure 1).

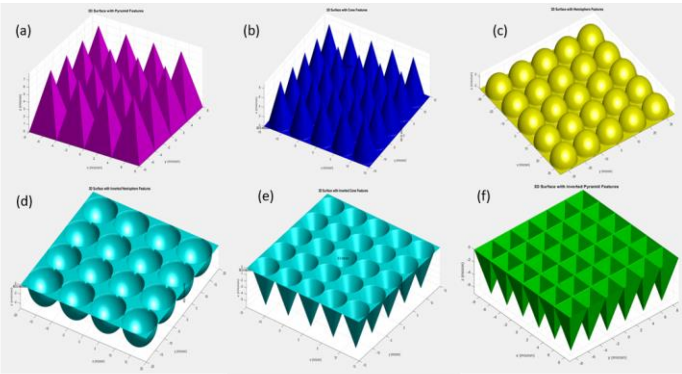


FIGURE 1: MICRO-TEXTURE DEVELOPED IN MATLAB: (A) PYRAMID PROTRUSION, (B) CONE PROTRUSION, (C) HEMISPHERE PROTRUSION, (D) HEMISPHERE CAVITY, (E) CONE CAVITY, AND (F) PYRAMID CAVITY.

To simulate the interaction of light with these textured surfaces, the surfaces are discretized into a mesh of triangular facets. Each facet is treated as a flat surface, with its own orientation defined by its surface normal. This approach allows for precise calculations of incident angles and reflection directions at each point of interaction.

2.2 Ray Tracing of Micro-structured Surfaces

The ray tracing technique traces the path of light rays as they interact with surfaces. The basis of ray tracing lies in geometric optics, which treats light as rays traveling in straight lines, with interactions governed by principles like reflection law and Fresnel equations [11].

In the simulation framework, codes for ray tracing loops are created which is pivotal for studying the interaction between light and the various micro-structured surfaces. The general approach across all six surface textures involves iterative calculations to track the light ray's path as it interacts with the surface. This process involves defining a light ray's initial position and direction vector. For all the micro-structures, the starting point is taken one micron above the top center point, so that all the rays coming from different angles passing through this point can be analyzed. Also, the initial direction of ray to track its path as it reflects off the surfaces can be given by the user in the form of initial incident angle. The algorithm solves the intersection point using the equations used for forming the textured planes and the ray's initial direction. If the intersection is found within the bounds of a textured surface, the normal at the intersection point is used to determine the angle of incidence, which, in turn, is used to calculate the reflected ray's direction based on the reflection law. The process accounts for the change in light intensity at each interaction, ensuring accurate representation of light behavior. Calculating the impact of these interactions is done iteratively until the ray exits the simulation domain or after a predefined number of interactions. The interaction, showcasing the incident and reflected rays, is shown in Figure 2, to provide a detailed representation of the ray tracing process for different textures.

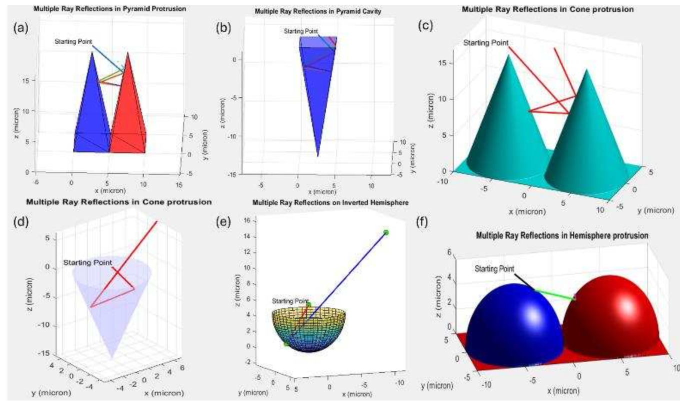


FIGURE 2: RAY TRACING OF MULTI-REFLECTION FOR: (A) PYRAMID PROTRUSION, (B) PYRAMID CAVITY, (C) CONE PROTRUSION, (D) CONE CAVITY, (E) HEMISPHERE CAVITY, AND (F) HEMISPHERE PROTRUSION.

2.3 Estimation of Light Absorption Considering Multi-reflection

For all texture types, estimation of light absorption at each interaction is performed in the ray tracing loop. Absorption is calculated based on the optical and material properties of silicon, where the refractive index and extinction coefficient vary with wavelength and are taken from the literature [14], and thickness is taken 0.0001m for thin film silicon solar cells from the literature [15]. The simulation framework implements absorption equation stepwise, first uses the Fresnel equations [11] to calculate reflectance and transmittance. After that, absorption is deduced from Kirchhoff's law [13] by using Beer-Lambert and Fresnel equations (equation 5), and the total absorption and remaining intensity of the ray are updated. The absorption at each interaction is stored in the absorptions array.

Throughout the ray tracing process, the model collects data on the interaction points, angles of incidence, angles of reflection, and absorption at each point. This data is crucial for analyzing how different microstructures interact with light and can be used to optimize the surface texture design for specific optical properties.

2.4 Framework for User Interface

For the optical simulation and analysis, the geometric configuration of micro-structured surfaces plays a pivotal role in dictating their interaction with light. The user is tasked with defining the dimensions of the microstructures. Additionally, the user specifies the number of microstructures along the X and Y directions, dictating the density and periodic arrangement of the shapes on the surface. No spacing between the texture features is considered in this study, to maximize the total area available for light absorption. Information regarding the initial incident light, specifically its angle with the vertical Z-axis, can be user-defined, providing a comprehensive framework for studying the optical behavior of the microstructures.

A comprehensive suite of codes, each dedicated to a unique type of texture and its corresponding ray tracing visualization and absorption estimation, has been developed. The main script, which functions as a centralized hub, integrating these individual MATLAB codes to provide a streamlined user experience and a unified platform for analysis, is also developed. This main script serves as the point for integration, allowing users to navigate effortlessly through different silicon micro-textures and observe their ray tracing behavior and estimate the light absorption due to multi-reflection.

Upon launching the simulation, a clear and concise menu is presented, listing out the available texture options. The script prompts users to input their choice, selecting the desired silicon texture for visualization, upon execution. The script accommodates a wide range of inputs, from pyramid, hemisphere, cone protrusions to cavities, ensuring versatility. Depending on the user's input, the script calls the associated function, crafted for the selected texture. These functions are self-contained units, encapsulating the required code for user interface generation, silicon texture rendering, ray tracing simulation, and light absorption calculation. This modular design ensures ease of maintenance and scalability, providing a robust foundation for future enhancements and additions.

As the selected function executes, users are presented with absorption results in command window and a representation of the silicon texture alongside its ray tracing simulation. This visual output serves as a crucial tool, connecting theoretical understanding with practical observation. Users gain the opportunity to closely examine the interaction between light rays and silicon texture, gaining valuable insights for further research and innovation. To visualize and interpret the interaction effects between light wavelength, incident angle, and absorption, a 3D surface plot is generated. This plot maps the total absorption on the vertical axis against the incident angle and wavelength on the horizontal plane. By utilizing color gradients, the plot distinctly illustrates how absorption varies, providing a clear visual representation of the optimal conditions for maximum absorption. This visualization not only helps in understanding the material's photonic behavior under varied conditions but also aids in identifying specific structure dimensions, wavelengths and angles that enhance absorption, which is critical for optimizing the material design for solar cell applications. Figure 3 provides an example of the 3D surface plot generated after completing the simulation.

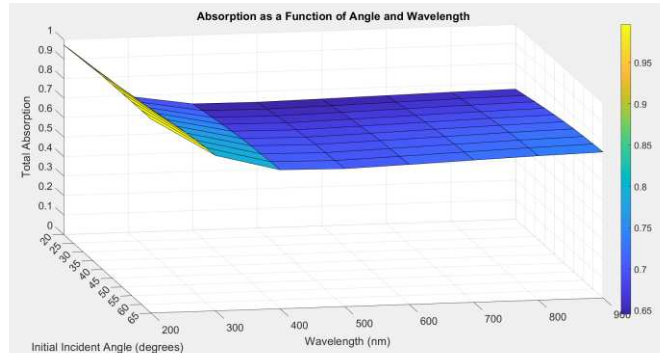


FIGURE 3: LIGHT ABSORPTION IN CONE PROTRUSION (RADIUS: 5 μm, HEIGHT: 25 μm).

In summary, the MATLAB-based user interface offers advanced ray tracing simulations that accurately model multiple light reflections within textured surfaces, allowing for precise analysis of light interactions. It supports versatile texture modeling, including pyramidal, conical, and hemispherical geometries, to evaluate their impact on light absorption. The user-friendly design ensures accessibility for researchers and engineers, while comprehensive visualization tools, such as 3D surface plots and ray tracing animations, illustrate how different textures affect absorption. Integrating material-specific properties enhances the accuracy of predictions, and the interface's validation against experimental data confirms its reliability. Additionally, it is adaptable for future enhancements, making it a powerful tool for optimizing light absorption in textured solar cell surfaces.

3. RESULTS AND DISCUSSION

3.1 Experimental Validation

To validate the multi-reflection angles obtained from the simulation, experimental validation is carried out focusing on pyramid protrusion and cavity structures. The primary aim is to validate the accuracy of the ray tracing models developed and implemented in the modeling framework, by comparing the simulation and experimental data on multi-reflection angle(s). The experimental setup comprised of camera, laser light and pyramid structure. The laser serves as the primary source of incident light. The pyramid structures are located centrally to act as the reflective surfaces for the laser beams. The camera is placed at a specific position to capture detailed images of the interaction between the laser beams and the pyramid structures. The pyramid protrusion (width: 5.08 cm, height: 3.81 cm) and cavity (width: 6.10 cm, height: 4.32 cm) structures are designed using Autodesk software and fabricated using 3D printing techniques. To validate the accuracy of the ray-tracing simulation framework developed in MATLAB, a laser beam is directed towards the structure at a specified angle during the experiment, then subsequent reflections on structure's surfaces are recorded using a digital protractor overlaid on the experimental images. As presented in Tables 1 and 2, the observed reflected angles from experiment match closely with those derived from the simulation, confirming the accuracy and reliability of the simulation framework developed in this study.

TABLE 1: EXPERIMENTAL AND SIMULATION REFLECTION ANGLE(S) COMPARISON FOR PYRAMID PROTRUSION.

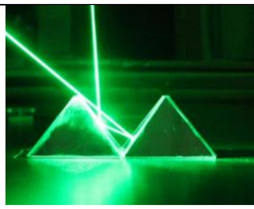
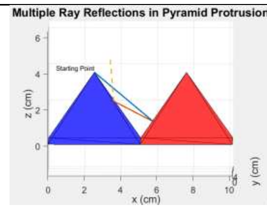
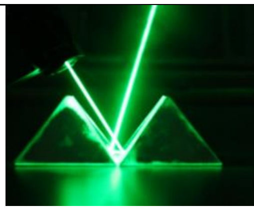
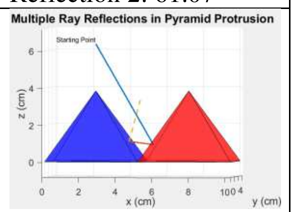
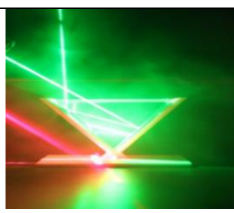
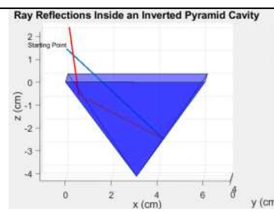
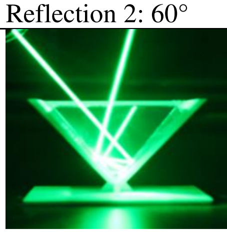
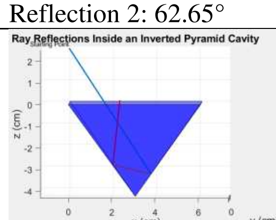
Incident angle	Experiment	Simulation
50°	 Reflection 1: 7° Reflection 2: 61°	 Reflection 1: 6.30° Reflection 2: 61.07°
30°	 Reflection 1: 26° Reflection 2: 41°	 Reflection 1: 26.30° Reflection 2: 41.07°

TABLE 2: EXPERIMENTAL AND SIMULATION REFLECTION ANGLE(S) COMPARISON FOR PYRAMID CAVITY.

Incident angle	Experiment	Simulation
47°	 Reflection 1: 8° Reflection 2: 60°	 Reflection 1: 7.78° Reflection 2: 62.65°
33°	 Reflection 1: 21° Reflection 2: 48°	 Reflection 1: 21.78° Reflection 2: 48.65°

In addition, the simulation results are compared with the literature [4] in which the plot showing 1-R-T (absorption) versus wavelength closely matches with the trends observed by using this MATLAB-based user interface. This comparison reinforces the accuracy and reliability of the interface developed.

3.2 Relationship between Microtexture and Light Absorption

In this study, wavelength range of 200-900 nm that encompasses a significant portion of the solar spectrum is taken. It should be noted that the optical properties of silicon vary with the wavelength, as the absorption coefficient increases significantly at shorter wavelengths (below 500 nm). Moreover, the initial incident angles range of 20°-65° is studied at 5° intervals to simulate a variety of solar positions experienced by solar cells during typical daytime conditions. This range allows for a comprehensive analysis of how different structures enhance light absorption across different solar angles, thereby aiming to optimize solar cell performance throughout the day.

Figures 4 and 5 show the absorption characteristics of pyramid protrusions and cavities, respectively, as a function of initial incident angle and wavelength for a fixed height of 5 µm and varying widths of 5 µm, 15 µm, and 25 µm. For both protrusion and cavity, the pyramid texture with 5 µm width shows the highest absorption across most wavelengths and incident angles. As the width increases to 15 µm and 25 µm in both protrusion and cavity, there is a noticeable drop in absorption. This is indicative of the fact that smaller texture enhances light absorption by reducing the reflectance and preventing rays from escaping, thus effectively trapping it within the structure through multiple reflection. Additionally, as the wavelength decreases, the overall absorption tends to increase. For shorter wavelengths, light absorption for these surfaces maximizes to the range of 0.94 to 0.98 due to combination of multiple reflection and material/optical properties.

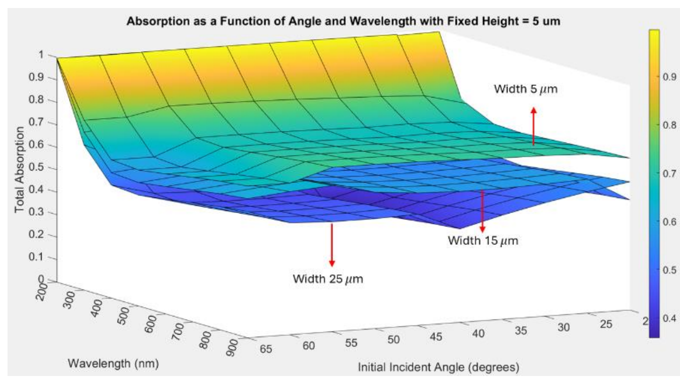


FIGURE 4: ABSORPTION IN PYRAMID PROTRUSION FOR A FIXED HEIGHT of 5 μm.

Figures 6 and 7 examine the light absorption in pyramid protrusions and cavities, respectively, across a range of wavelengths and initial incident angles for a fixed height of 25 µm and varying widths (5 µm, 15 µm, and 25 µm). The absorption generally decreases as the wavelength increases, suggesting that the shorter wavelengths can be trapped more effectively (absorption increasing up to 0.98). A notable observation is that the absorption is maximized at the lowest incident angles and at height-to-width ratio 1:1 (width of 25 µm). Additionally, the difference between the surface plots showing absorption for various widths decreases as the fixed height increases. Similar observation can be made for a fixed height of 15 µm with varying widths.

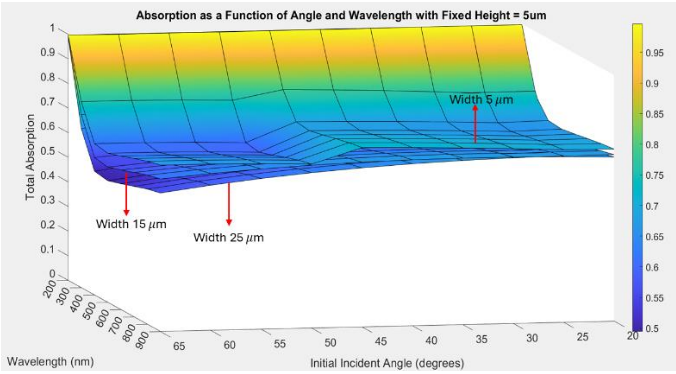


FIGURE 5: ABSORPTION IN PYRAMID CAVITY FOR A FIXED HEIGHT OF 5 μm.

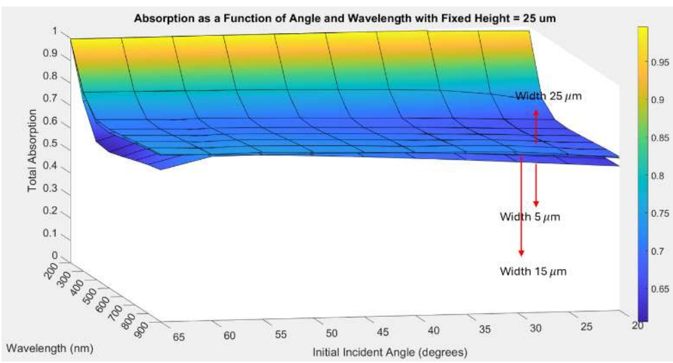


FIGURE 6: ABSORPTION IN PYRAMID PROTRUSION FOR A FIXED HEIGHT OF 25 μm.

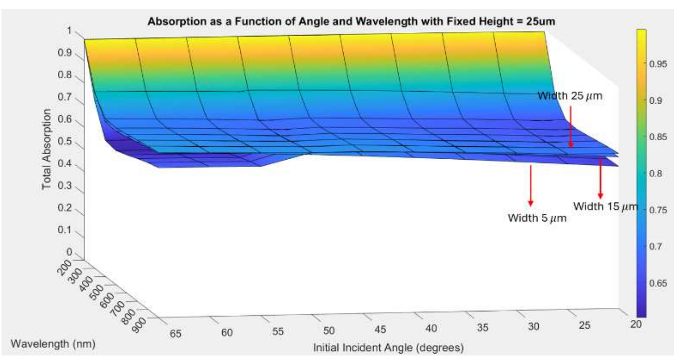


FIGURE 7: ABSORPTION IN PYRAMID CAVITY FOR A FIXED HEIGHT OF 25 μm.

For a fixed width and varying heights for pyramid microtexture, the light absorption trend follows complete opposite trend (the difference between the surface plots showing absorption for various height increases as the fixed width increase) compared to the fixed height results discussed earlier. Therefore, the results are not shown to avoid redundancy.

Figures 8 and 9 examine the absorption characteristics of cone-shaped microstructures for protrusions and cavities, respectively, across a range of wavelengths and initial incident angles for a fixed height of 5 µm and varying base radii of 5 µm, 15 µm, and 25 µm. For cone cavity, as the initial incident angle increases, the total absorption generally decreases across all wavelengths. However, the trend is not straightforward for protrusion texture. Additionally, total absorption decreases as the wavelength increases. Similar trend can be seen for fixed heights of 15 μm and 25 μm with variation in base radii, however, the difference between the surface plots showing absorption for various radii decreases.

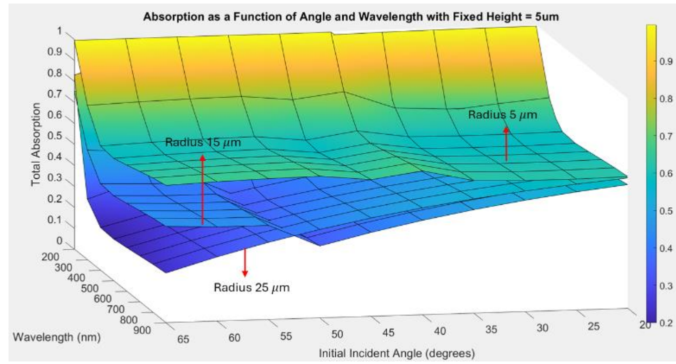


FIGURE 8: ABSORPTION IN CONE PROTRUSION FOR A FIXED HEIGHT OF 5 μm.

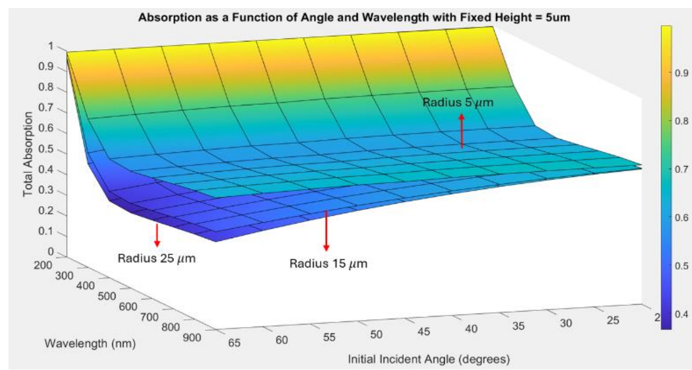


FIGURE 9: ABSORPTION IN CONE CAVITY FOR A FIXED HEIGHT OF 5 μm.

For a fixed base radius and varying heights for cone-shaped microtexture, the light absorption trend follows complete opposite trend compared to the fixed height results discussed earlier. Therefore, the results are not shown to avoid redundancy.

Figures 10 and 11 show the overall absorption of hemispherical protrusions and cavities, respectively, at varying wavelengths and incident angles at radii of 5 µm, 15 µm, and 25 µm. For both hemispherical protrusion and cavity, the absorption generally decreases with increasing wavelength across all radii. Hemispherical protrusions show no consistent trend. However, hemispherical cavity shows a consistent trend with little variations with dimensions which is the result of multiple reflections, as all the reflected angles for any initial incident angles are converging towards the focal point or the centroid of the hemisphere cavity, which make them closer to the surface normal and resulting in higher absorption. In summary, the geometry of the hemispherical cavity causes the rays to converge towards the center, leading to similar angles of incidence for subsequent reflections. This, combined with the physics of reflection, transmission, and absorption at material boundaries, results in almost the same values for different incident angles.

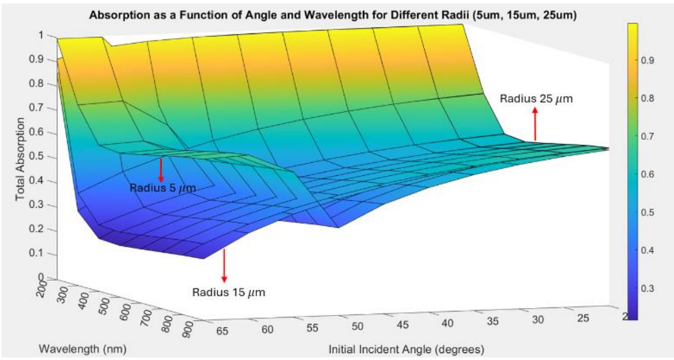


FIGURE 10: ABSORPTION IN HEMISPHERE PROTRUSION.

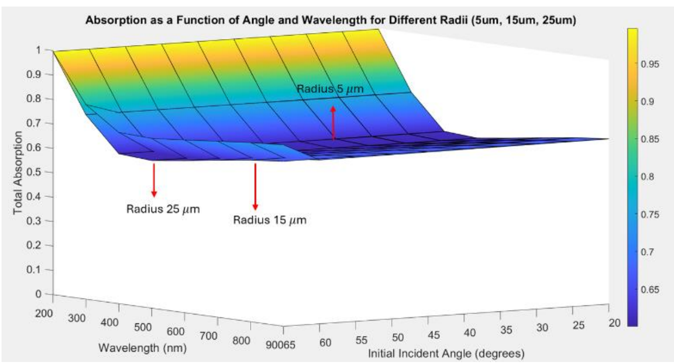


FIGURE 11: ABSORPTION IN HEMISPHERE CAVITY.

4. CONCLUSION

In this study, a MATLAB-based user interface has been developed to facilitate diverse users in assessing the absorption of sunlight in silicon-based solar cells having top layer as a microtextured surface. The user interface employed a multi-faceted mesh-grid algorithm to design six distinct 3D textural surface geometries. Advanced ray tracing simulations that identify points of light intersection on these textures and ascertain the trajectory of light upon reflection were also implemented in the modeling framework. The user interface was able to simulate and analyze the complex phenomenon of multiple light reflections within the structure, and estimate the overall light absorption based on the multi-reflections. The user interface allows the user to visualize 3D surface textures, ray tracing of the light following initial incidence and multi-reflection at various incident angles, and a surface plot that provides information on light absorption with variation in wavelengths and initial incident angles for a particular texture geometry and dimension. This holistic approach allows comprehensive understanding of the effect of surface texturing on light absorption.

After developing the MATLAB-based user interface, experimental results obtained from laser ray interactions showed a high degree of similarity with simulation predictions, validating the modeling framework developed in the study. After experimental validation, the numerical framework was used to investigate the relationships between light absorption and surface texture geometry and dimensions for pyramid, cone and hemisphere protrusion and cavity microstructures for silicon material. The results showed that, in general, as the wavelength decreases, the overall absorption increases. The relationship between texture dimension and overall light absorption is not straightforward and depends on the texture type and geometry. However, the cavity texture provides more consistent light absorption compared to its protrusion counterpart. Furthermore, it is evident that the hemisphere cavity structure offers superior performance in terms of light absorption consistency. This consistency is a key indicator of the structure's potential for applications where uniform absorption is critical, regardless of the angle of incident light.

For future work, impact of surface textures on the absorption as well as transparency of transparent solar cells can be investigated. Long-term performance and durability of textured surfaces, particularly their self-cleaning capabilities under real-world conditions, can be studied to ensure practical viability and sustained efficiency. Experimental studies on how much the efficiency and power output of a solar panel are improved with the addition of surface texture can be conducted in the future as well.

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