

Smart Solar Surfaces: Investigating the Effect of Surface Texture on Photovoltaic Efficiency

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Abstract: The efficiency of photovoltaic (PV) systems is strongly influenced by the amount of solar radiation that reaches the active semiconductor surface. A significant fraction of incident sunlight can be lost through reflection at the air–glass or air–semiconductor interface before it contributes to electricity generation. Surface texturing is an important optical-engineering approach for reducing reflection and increasing light trapping within photovoltaic devices. This study proposes an experimental investigation into the effect of surface texture on photovoltaic performance by comparing solar cells or small PV modules having different surface morphologies. A smooth reference surface is proposed to be compared with micro-textured and more strongly textured surfaces under controlled illumination conditions. Electrical parameters including voltage, current, output power and conversion efficiency would be measured, while surface characteristics such as texture type, approximate feature size and surface roughness would be documented. The underlying mechanism is based on multiple reflections and increased optical path length: appropriately designed textures can redirect incident light into the absorbing layer and reduce front-surface reflection. However, excessive or poorly controlled roughness may introduce optical, electrical or manufacturing disadvantages. The proposed study therefore aims not simply to maximize roughness but to identify a surface texture that provides an effective balance between light trapping, optical transmission and photovoltaic electrical output. The research is relevant to the development of smart solar surfaces that can improve energy harvesting without requiring a fundamental change in the photovoltaic material itself.

Keywords: *photovoltaic efficiency, surface texture, solar cell, light trapping, reflectance, textured surface, optical absorption, smart solar surface.*

1. Introduction: The increasing demand for clean and sustainable energy has intensified research into technologies capable of converting renewable resources into useful electricity. Solar photovoltaic technology is one of the most important renewable-energy technologies because it directly converts incident solar radiation into electrical energy. However, the electrical output of a photovoltaic device is influenced by several optical, electrical and environmental losses. Among the optical losses, reflection at the front surface is particularly important because photons that are reflected away from the device cannot contribute to photocurrent.

The interaction between light and a photovoltaic surface is therefore an important area of photovoltaic research. Conventional flat surfaces provide a relatively simple interface between

air and the photovoltaic material, but the difference in refractive index can cause a significant portion of incident radiation to be reflected. Surface texturing provides a means of modifying this interaction. Instead of presenting a single planar interface, a textured surface contains geometrical features such as pyramids, inverted pyramids, grooves, random microstructures or sub-wavelength structures. These features can change the direction of incident and reflected light and increase the probability that light enters and remains within the absorbing material. Textured silicon surfaces are particularly well established in crystalline-silicon photovoltaic technology. Pyramidal textures produced through anisotropic etching can reduce surface reflection and increase light trapping. Studies of pyramidal structures have demonstrated that the geometry and uniformity of the texture influence optical reflectance.

The fundamental principle is that a textured surface can give reflected light another opportunity to enter the photovoltaic device. In addition, the distribution of surface angles can randomize the direction of light inside the absorber and increase the optical path length. These effects can improve the absorption of useful wavelengths and consequently contribute to higher photocurrent.

Recent developments have extended surface texturing from conventional micrometre-scale pyramids to submicron and nanoscale structures. Such structures can provide broadband and wide-angle antireflection properties. Research on nanostructured antireflective surfaces has shown their potential for solar cells and other optoelectronic devices.

Nevertheless, surface texture alone does not automatically guarantee improved photovoltaic efficiency. Texture geometry, feature dimensions, surface uniformity, incident angle, wavelength, coating characteristics and electrical properties all influence the final device performance. For example, recent research has shown that the surface morphology can influence not only light trapping but also metallization and recombination-related effects.

Therefore, the present study focuses on the relationship between surface texture and photovoltaic efficiency. The proposed work investigates whether controlled modification of surface texture can improve electrical output compared with a relatively smooth reference surface.

2. Background and Theoretical Basis

2.1 Photovoltaic conversion:

A photovoltaic cell converts solar radiation into electrical energy through the photovoltaic effect. When photons with sufficient energy are absorbed by a semiconductor, electron-hole pairs can be generated. The internal electric field of the device separates these charge carriers, allowing an external electrical circuit to collect the resulting current.

The electrical power generated by a photovoltaic device can be expressed as:

$$P = VI$$

where:

- P = electrical output power,
- V = output voltage,
- I = output current.

The conversion efficiency of a photovoltaic device can be expressed as:

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

where P_{out} is the electrical power generated and P_{in} is the incident solar power.

Consequently, increasing the amount of useful radiation absorbed by the active material can potentially increase the generated electrical power.

2.2 Optical reflection at a flat surface: When light travels from one medium to another with a different refractive index, part of the incident radiation may be reflected. A flat photovoltaic surface therefore represents an optical loss mechanism.

A simple flat interface has a relatively uniform surface normal. Consequently, reflected light tends to leave the device without interacting further with the absorber. Surface texturing changes this situation by introducing many local surface orientations.

2.3 Surface texturing and light trapping: Surface texturing can be understood as a form of optical management. Pyramid-shaped textures are widely used in crystalline-silicon solar cells because they can produce multiple reflections and improve light coupling into the silicon.

Consider a photon incident on a textured surface. Instead of being reflected directly away from the device, it may encounter another facet of the texture and be redirected toward the absorbing region. Repeated interactions increase the probability of absorption.

This phenomenon is commonly described as light trapping.

The optical path length can also be increased by texture-induced changes in the propagation direction. For thin photovoltaic absorbers, this effect can be particularly important because the available absorbing thickness is limited. Reviews of light trapping in silicon solar cells identify pyramidal texturing as one of the principal approaches for increasing optical path length.

2.4 Texture geometry: Surface textures can be classified as smooth/planar, micro-textured, pyramidal, inverted-pyramidal, random rough, and submicron or nanostructured surfaces. The optimum texture depends on the photovoltaic material and its required optical properties, as surface morphology can significantly influence light reflection and absorption.

2.5 Texture and antireflection: Surface texture can function independently as an antireflective structure or in combination with an antireflection coating. The combination is particularly important in high-performance photovoltaic devices.

A textured surface changes the effective optical interface and may cause multiple reflections. Antireflection coatings can further reduce reflection through interference and refractive-index engineering. Research on textured silicon solar cells has therefore investigated the optimization of coatings together with surface morphology.

3. Objectives of the Study:

- To investigate the effect of different surface textures on photovoltaic electrical output and efficiency.
- To compare the performance of smooth and textured photovoltaic surfaces in terms of voltage, current, and power generation.

- To identify the surface texture that provides the most effective improvement in solar-energy harvesting.

4. Materials and Methods:

4.1 Research Design: An experimental comparative design will be used to investigate the effect of surface texture on photovoltaic performance. Four photovoltaic samples will be compared under controlled illumination: Sample A with a smooth/reference surface, Sample B with fine texture, Sample C with medium texture, and Sample D with coarse or strongly textured surface. The electrical performance of each sample will be measured and compared under identical experimental conditions.

4.2 Materials: The experimental setup will require identical small photovoltaic cells or PV modules, a controlled solar simulator or stable light source, digital multimeter, ammeter, voltmeter, variable electrical load, irradiance meter, thermometer, measuring scale, mounting frame, connecting wires, textured samples, a smooth reference sample, and a data-recording system. The surface textures will be prepared or selected with controlled characteristics to ensure meaningful comparison.

4.3 Experimental Variables: The independent variable will be the surface texture or morphology of the photovoltaic surface. The dependent variables will include output voltage, output current, electrical power, and photovoltaic conversion efficiency. Solar irradiance, exposure duration, temperature, cell area and type, electrical load, sample orientation, light-source distance, measuring instruments, testing time, and wiring arrangement will be kept constant as far as practically possible.

5. Experimental Procedure: The photovoltaic samples will first be cleaned and inspected for visible defects. Each sample will then be mounted at a fixed angle and distance from a constant light source. Incident irradiance and surface temperature will be recorded, followed by measurement of open-circuit voltage and short-circuit current. The samples will be connected to a variable electrical load, and voltage and current will be recorded under different load conditions. Output power will be calculated, and the maximum power and conversion efficiency will be determined. The same procedure will be repeated for all surface textures, with repeated measurements used to obtain reliable mean values for comparison.

6. Measurement of Photovoltaic Efficiency

For a photovoltaic sample of area A , the incident solar power can be expressed as:

$$P_{in} = G \times A$$

where:

- G = incident irradiance in W/m^2 ,
- A = active area of the photovoltaic sample in m^2 .

The output power is:

$$P_{out} = V \times I$$

Therefore:

$$\eta = \frac{V \times I}{G \times A} \times 100$$

For maximum-power analysis:

$$P_{max} = V_{mp}I_{mp}$$

where V_{mp} and I_{mp} are the voltage and current at the maximum power point. This allows the performance of each texture to be compared quantitatively.

7. Proposed Data-Analysis Method

The measurements should be organized according to surface type.

For each sample, the following parameters should be calculated:

- Mean voltage
- Mean current
- Maximum power
- Mean conversion efficiency
- Percentage improvement relative to the smooth reference

The percentage improvement can be calculated as:

$$\% \text{ Improvement} = \frac{\eta_{\text{texture}} - \eta_{\text{reference}}}{\eta_{\text{reference}}} \times 100$$

If sufficient repeated measurements are obtained, statistical analysis such as one-way ANOVA may be used to determine whether differences among surface groups are statistically significant.

Correlation analysis can also be performed between a quantitative texture parameter, such as average roughness, and photovoltaic efficiency.

8. Consolidated Experimental Framework:

Surface condition	Expected optical behaviour	Main parameter measured	Expected photovoltaic response	Research purpose
Smooth/reference	Higher direct reflection	Voltage, current, power, efficiency	Baseline performance	Reference comparison
Fine texture	Reduced reflection; increased light coupling	Voltage, current, power, efficiency	Possible improvement	Evaluate mild texturing

Medium texture	Greater multiple reflection and light trapping	Voltage, current, power, efficiency	Potentially highest performance	Identify optimum texture
Coarse/strong texture	Strong surface scattering; possible additional optical losses	Voltage, current, power, efficiency	May improve or decline depending on geometry	Determine whether excessive texture is beneficial

Table 1. Proposed relationship between surface morphology and photovoltaic performance.

9. Expected Results and Discussion

It is expected that the textured photovoltaic surfaces will demonstrate different electrical outputs compared with the smooth reference surface.

The principal expected mechanism is reduction of optical reflection. A textured surface presents multiple orientations to incoming radiation. Some radiation that would otherwise be reflected from a flat surface may undergo additional interactions with the textured structure and subsequently enter the photovoltaic absorber.

Pyramidal structures are particularly relevant because their geometry can redirect incident radiation and promote multiple reflections. Previous investigations have shown that pyramid morphology and processing conditions influence optical reflectance.

The fine-textured sample is expected to show some improvement over the smooth surface if its geometry is appropriately matched to the wavelength range and photovoltaic material. However, the magnitude of improvement may be relatively small.

The medium-textured sample is hypothesized to provide the best balance between reflection reduction and light trapping. This expectation is based on the principle that an appropriately engineered texture can increase the optical path length without creating excessive surface irregularity.

The coarse-textured sample may demonstrate a more complicated response. Greater roughness does not necessarily mean greater efficiency. If texture features become too large, irregular or poorly matched with the optical design, scattering may increase without producing a corresponding increase in useful absorption.

Therefore, the expected relationship between texture and efficiency is not necessarily linear. Instead, an optimum texture range may exist.

This concept is consistent with modern photovoltaic research in which surface morphology is treated as an optical-design parameter rather than simply as a measure of roughness. Recent research on submicron silicon textures has demonstrated that carefully engineered texture can improve optical performance across a broad wavelength range.

The results should also be interpreted in relation to temperature. Photovoltaic electrical performance can vary with temperature, so comparisons must be performed under closely controlled thermal conditions.

Another important consideration is soiling. Outdoor PV surfaces accumulate dust and other particles, which can reduce light transmission. Reviews published in recent years identify soiling as a significant contributor to PV performance loss.

Conclusion: The proposed study investigates surface texture as an important design parameter for improving photovoltaic performance. The fundamental premise is that an appropriately engineered surface can reduce front-surface reflection, redirect incident radiation and increase the optical path length within the photovoltaic absorber.

Existing research provides strong theoretical and experimental support for the use of textured surfaces, particularly pyramidal structures, in crystalline-silicon photovoltaic devices. However, the relationship between texture magnitude and actual electrical efficiency is not necessarily linear. An excessively rough or poorly designed surface may not provide the optimum result.

The proposed experimental comparison of smooth, fine-textured, medium-textured and strongly textured surfaces will therefore help identify the texture that provides the best balance between optical coupling and electrical output.

The concept of a smart solar surface extends beyond simple antireflection. A future optimized surface could simultaneously provide light trapping, antireflection, self-cleaning and environmental durability. Such multifunctional surfaces could contribute to higher and more stable solar-energy production while minimizing the need for active energy-consuming interventions.

Overall, surface engineering represents a promising pathway for improving photovoltaic performance without fundamentally changing the underlying energy-conversion mechanism. The proposed research can provide an experimentally accessible framework for investigating how controlled surface morphology influences solar-energy harvesting.

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