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REGULAR ARTICLE

Examining Substrate Morphology and Electrical Characteristics of Nanostructured Silicon Solar Cells

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The morphology of the substrate plays a vital role in determining the electrical performance of nanostructured silicon solar cells (NSiSC) by influencing charge transport dynamics, optical absorption, and surface recombination. The research aims to investigate the influence of different substrate morphologies on the electrical characteristics of NSiSC, including Power Conversion Efficiency (PCE), Short-Circuit Current (SCC), Fill Factor (FF) and open-circuit voltage (Voc). NSiSC was fabricated using substrates with varying surface roughness and textures. Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) were utilized to characterize surface morphology. X-Ray Diffraction (XRD) analysis was performed to examine crystalline quality and phase composition. Optical reflectance spectra were recorded to evaluate light absorption efficiency. Electrical performance was measured under standard illumination conditions using a solar simulator. The findings reveal a strong correlation between substrate morphology and the electrical properties of the solar cells. Rougher surfaces demonstrated enhanced light trapping, leading to increased SCC density. Compared to planar substrates, nano-patterned surfaces exhibited higher SCC density increased VOC and enhanced PCE. NSiSC-30/150 had the highest PCE (13.5%), with an open-circuit voltage of 529 mV, an FF of 67.5 %, and an SCC of 37.8 mA/cm^2.

Keywords: Substrate Morphology, Electrical Character, Nanostructure, Silicon Solar Cells, Light Absorption Efficiency.

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1. INTRODUCTION

The process of conversion of the sunlight into the electricity is referred to as Solar Cells (SCs), which have gained popularity in present years, as they denote the most essential approach to employ Renewable Energy (RE) to satisfy societal growth requirements when also relieving the pressures of environmental degradation. Flexible electronic devices have been identified as a fundamental component in everyday life due to their lightweight, elasticity and mobility [1]. Developing SC technologies that employ complicated and sophisticated materials such as dye-sensitized, multijunction, quantum dot, perovskite and organic were established to tackle the problems for conversion effectiveness and toughness [2].

Photovoltaic (PV) technology is an economical, clean, renewable, and dependable form of electricity generation for both the applications of the space and terrestrial due to the endless availability of solar radiation. As silicon is abundant in the earth's crust, stable over the long term, has proven technology, and is reasonably priced, it is expected to continue to be the most popular PV material

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for the foreseeable future despite all of the alternatives and the extensive research being done in this field [3]. Silicon Solar Cells (SiSC) have become the most modern, effective and technologically mature SCs available on the market. SiSC's outperform other types of solar cells in terms of PCE and stability. TSSC reduces silicon SC production costs, as well as carrier migration distance and recombination. While silicon thickness is an important aspect in maximizing light absorption, a balance must be maintained. A thin silicon layer might lead to poor light absorption [4].

The Substrate Morphology (SM) is another crucial factor that impact Sb_2Se_3 grain development and orientation. Using this method, users can choose the most desirable substrate material (for electrical matching) and then utilize the SM to determine the chosen development direction and bulk morphology [5]. Some of the NSiSC such as Silicon Nanowires (SiNWs) and Porous Silicon (PS), have sparked widespread interest due to their observable luminescence at ambient temperature. Because of their crucial chemical and physical features, SiNWs and PS could be employed in a variety of sectors, including optoelectronics, gas sensors, and photovoltaics [6].

2. RELATED WORKS

Using a textured silicon substrate and substituting Poly-Dimethylsiloxane (PDMS) for glass to boost light absorption and decrease reflection, the research [7] improved the performance of nanostructured PSCs. Analysis of a simulated unit cell and a discussion of manufacturing techniques are presented. J_{sc} (SCC) reaches 22.28 mA/cm^2, indicating a 32 % increase in efficiency. Limitations include flaws in the fabrication that impair the consistency of performance. Ethylenediamine (EDA) concentration was used in [8] to optimize ZnO hierarchical designs for improved Dye-Sensitized SC (DSSC) efficiency. ZnO nanostructures were created using a low-temperature hydrothermal process, and their shape, bandgap, and dye-loading ability were examined. The results demonstrate enhanced photovoltaic conversion (~ 4.42 %) and photon-to-current efficiency (~ 46.6 %). Potential scalability and stability problems that might impair long-term DSSC performance are among the limitations.

Polycrystalline si SC's PCE was enhanced [9] by applying an Anti-Reflection Coating (ARC) made of $ZnAlO_4$ (gahnite) spinel nanostructure. Through the use of radio frequency magnetron sputtering, transparent gahnite nano-microfilms were created. Under regulated conditions, the PCE of 23.83 % was attained by the optimum coating (35 min). Limitations include possible long-term stability issues with the ARC material and restrictions on deposition. Thin-film organic photovoltaics with improved light absorption at different incidence angles were created for distributed solar applications [10]. Sequential processing was used to create and examine all-polymer SCs with a hierarchical shape. The effectiveness is a record 19.06 %, and the power gain over flat devices is 30 %, according to the data. But there are drawbacks, such as possible scaling issues and material stability issues.

By employing periodic nanotextures, the work [11] improved the efficiency of perovskite–silicon tandem SCs. The technique incorporated nanotextures to enhance optoelectronic characteristics and decrease reflection losses without sacrificing the quality of perovskite films. The results showed an increase in manufacturing yield from 50 % to 95 %, a confirmed 29.80 % efficiency, and a 15 mV increase in Voc. The challenges of optimizing layer thickness and potential problems with material stability are among the disadvantages. Femtosecond Pulsed Laser Deposition (fs-PLD) was used [12] to observe the impact of substrate temperature on the structural, optical and electrical properties of the TiO_2 thin films. According to the results, bandgaps and resistivity both reduce with temperature. Phase control restrictions and potential substrate interference are two examples of limits that affect precise material optimization. The influence of substrate engineering and active layer processing on the Bulk-Heterojunction (BHJ) shape of Organic SCs (OSCs) was examined [13].

3. EXPERIMENTAL METHODOLOGY AND PROCEDURES

This section outlines the materials, fabrication process, and characterization methods employed to examine the impact of substrate morphology on the electrical performance of nanostructured silicon SCs. SM, crystalline quality, optical absorption, and electrical properties were measured using a range of analytical tools such as AFM, XRD, and reflectivity measurements.

3.1 Material

All the reactions were carried out at the room temperature. Tetrafluoroboric acid (HBF_4), potassium permanganate ($KMnO_4$), and silver acetate ($AgC_2H_3O_2$) were used. The Czochralski-grown (CZ) *n*-type silicon (100) wafers which are known as CZ *n*-Si (100) were ultrasonically cleaned in acetone and deionized water for 10 minutes at the room temperature after being cut into 1.0×1.0 cm^2 pieces that having a resistivity of 0.001 to 0.005 Ω cm. Acetone and deionized water were used to ultrasonically clean textured NSiSC for ten minutes.

3.2 Experimental Conditions for Metal-Assisted Chemical Etching of Silicon and Nanostructured Silicon Solar Cells

Wet etching was executed by immersing the CZ n-Si (100) *n*-type and NSiSC in a mixture of HBF_4 (5M) and $AgC_2H_3O_2$ (5 % m/m) at room temperature for a specific time is considered as Stage 1. The samples were then transferred to a second solution of $KMNO_4$ (5 % m/m) and HBF_4 (5M) for durations ranging from 0 s, 30 s, 90 s, 150 s, and 210 s is considered as Stage 2. Table 1 represents the experimental conditions for Metal-Assisted Chemical Etching (MACE) on

Silicon Substrates and SCs. After the etching procedure, the samples were cleaned with the deionized water before further characterization.

Table 1 – Experimental Conditions for MACE on Silicon Substrates and Nanostructured Silicon Solar Cells

Substrate	Stage 1 ($AgC_2H_3O_2$/ HBF_4) [s]	Stage 2 ($KMnO_4$/ HBF_4) [s]	Sample Name
CZ n-Si (100)	10	0	CZ-Control
	20	30	CZ-20/30
	25	90	CZ-25/90
	30	150	CZ-30/150
	35	210	CZ-35/210
Nanostructured Silicon Solar Cell	10	0	NSiSC-Control
	20	30	NSiSC-20/30
	25	90	NSiSC-25/90
	30	150	NSiSC-30/150
	35	210	NSiSC-35/210

3.3 Atomic Force Microscopy (AFM)

The SM of the SiO_2/SiNWs/c-Si structure was examined using AFM in tapping mode using a WiTec Alpha 300 AR microscope. A 5×5 μm^2 scanned region was employed for analysis, and imaging was done using a silicon cantilever tip. The SM and changes in roughness before and after SiO_2 deposition were revealed by the AFM analysis.

3.4 Scanning Electron Microscopy (SEM)

Using SEM, the etched silicon samples' surface and cross-sectional morphology were investigated. The images obtained from the SEM provide comprehensive information on the etched Si surfaces' depth profiles, porosity, and nanostructure development. The investigation was carried out for etching periods of 60, 120, and 180 seconds, enabling comparison of structural alterations and surface roughness at various time points.

3.5 X-Ray Diffraction (XRD)

A Rigaku SmartLab X-ray diffractometer equipped with a high-resolution multi-layer mirror and Cu Kα radiation (λ = 1.54056 Å) was utilized to conduct XRD. For silicon samples etched for 60, 120, and 180 seconds, as well as a reference unetched sample, the diffraction patterns were recorded spanning the $20° \leq 2\theta \leq 80°$ range. Analysis was done on the MACE process's structural changes, crystallinity, and existence of residual Ag phases.

3.6 Reflectivity

A spectrophotometer in total reflectance mode (combining the specular reflection and the diffuse) was used to acquire optical reflectance spectra. The wavelength of the spectrum was 550 nm. To assess light absorption properties, the spectral reflectance of CZ n-Si (100) wafers and NSiSC was examined. The samples were sequentially exposed to $AgC_2H_3O_2$/HBF_4 solution for 18 s and then submerged in $KMnO_4$/HBF_4 solution for 0 s, 30 s, 90 s, 150 s, and 210 s, respectively, before reflectance measurements were performed.

4. RESULT

The objective is to examine how different SMs affect the electrical properties of NSiSC. NSiSC was made from substrates with different surface roughness and textures. The SM was characterized using AFM and SEM. To examine the crystalline quality and phase composition, XRD analysis was used.

4.1 Investigation of Substrate Morphologies on Electrical Characteristics of NSiSC

The impacts of various substrate morphologies on the electrical properties of NSiSC such as FF, SCC, Voc and PCE were assessed and shown in Table 2.

Table 2 – Measurement of NSiSC Parameters under AM 1.5 Irradiance

Sample	SCC (mA/cm^2)	FF (%)	Voc (mV)	PCE (%)	$\Delta\eta$
CZ- control	36.9	67.0	525	12.7	0.0
CZ-20/30	36.9	68.3	527	13.3	0.6
CZ-25/90	37.1	68.7	530	13.4	0.6
CZ-30/150	37.8	67.5	529	13.5	0.8
CZ-35/210	36.8	69.1	524	13.2	0.5
NSiSC-control	36.9	67.0	525	12.7	0.0
NSiSC-20/30	36.9	68.3	527	13.3	0.6
NSiSC-25/90	37.1	68.7	530	13.4	0.6
NSiSC-30/150	37.8	67.5	529	13.5	0.8
NSiSC-35/210	36.8	69.1	524	13.2	0.5

The measurement of NSiSC properties under AM 1.5 irradiance is shown in Table 2, which compares various CZ and NSiSC samples. While the FF and Voc exhibit minor fluctuations between samples, the SCC is largely constant. With changes, the PCE gets better; the CZ-30/150 and NSiSC-30/150 showed the largest gain, 0.8 %. According to these findings, structural alterations boost efficiency; the most notable gains were shown in CZ-30/150 and NSiSC-30/150.

4.2 Atomic Force Microscopy (AFM)

The SM of the SiO_2/SiNWs/c-Si structure was examined using AFM in tapping mode. When SiO_2 was deposited on silicon nanowires (SiNWs), as shown in Fig. 1, the surface roughness increased significantly, creating an organized nanostructure that was favorable for light trapping. For every structure, the root mean square (RMS) roughness is 180 nm. Improved optical qualities are suggested by the increased surface roughness, especially for use in photovoltaic and optoelectronic systems.

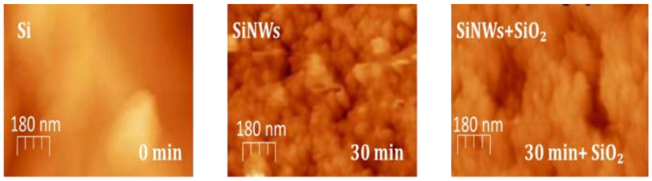

Fig. 1 – AFM images of Etching time vs SiNWs before and after deposition of SiO_2

4.3 SEM

The Au NPs could possibly nucleate and re-deposit onto the SiNWs surface, causing a distinct lateral etching that encourages SiNW degradation and fracture and the creation of porous structures along the sidewalls. SiNW length variation as a function of etching time is seen in Table 3.

Table 3 – Variation of the etching time versus SiNWs lengths

Etching Time (min)	Si Nanowires Length (μm)
12	5.5
24	8.2
36	4.8
48	3.4

The development of vertically aligned SiNWs is demonstrated by cross-sectional SEM images in Fig. 2, irrespective of the etching duration. If the etching period is varied from 12 to 48 minutes, the SiNWs length could exhibit a non-linear relationship. Furthermore, the length of the SiNWs increases from around 5.5 μm to approximately 8.2 μm when the etching period is extended from 12 to 24 minutes. During comparatively brief etching times (12 – 24 min), the Au NPs settle near the bottom of the SiNWs, exactly at the surface of the substrate, which promotes the development of more vertically oriented SiNWs. However, etching intervals longer than 36 minutes resulted in a reduction in SiNWs length (3.4 μm for 48 min etching).

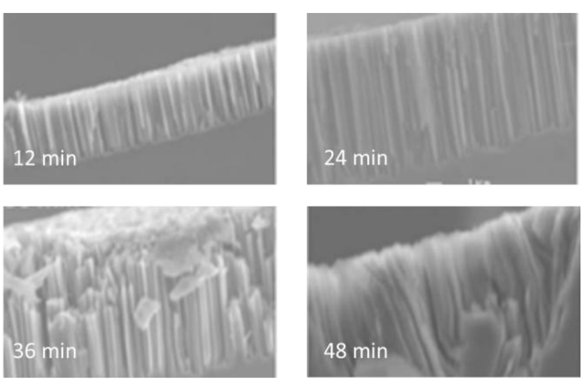

Fig. 2 – SEM cross-section images of etching time versus SiNWs

4.4 X-Ray Diffraction (XRD) Spectrum

The crystalline characteristics of silicon substrates are shown in the XRD patterns both before and after etching. The crystal orientation has been confirmed by the peaks at CZ *n*-Si (100), and leftover silver from the MACE procedure is shown by additional peaks from Ag_2O (Silver(I) Oxide). Non-porous silicon and etching times of 30 s, 90 s, and 150 s are represented by the samples. Wider peaks at longer etching times indicate structural changes and possible strain consequences from increasing porosity. Fig. 3 represents the XRD spectrum of the Silicon Substrate before and after the etching time.

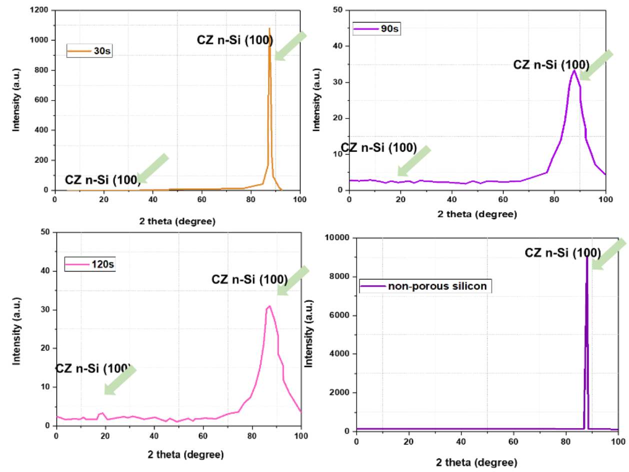

Fig. 3 – XRD spectrum of Silicon Substrate

5. DISCUSSION

The NSiSC outperformed the CZ *n*-Si (100) control samples in terms of PCE with NSSC-30/150 achieving the maximum efficiency (13.5 %), which could be assigned to better light absorption and surface modification. The enhanced etching conditions resulted in a small rise in the SCC (37.8 mA/cm^2) and the V_{oc} (529 mV), but the FF remained consistent. The SiNW length varies with etching time, reaching a peak of 8.2 μm at 24 min and decreasing at longer durations (3.4 μm at 48 min), indicating an ideal etching window for controlled nanostructure production. These findings demonstrate that the fine adjustment of etching conditions has a major influence on SC performance. The observed efficacy increase emphasizes the promise of nanostructured silicon for better solar applications.

6. CONCLUSION

The research determined that substrate shape has a substantial impact on the electrical performance of NSiSC. Increased surface roughness and nano-patterned textures increased light trapping, resulting in higher SCC density and conversion efficiency. The NSiSC-30/150 had the maximum efficiency (13.5 %) with an SCC of 37.8 mA/cm^2, a V_{oc} of 529 mV and an FF of 67.5 %. The longest silicon nanowire (8.2 μm) was obtained after 24 minutes of etching, whereas longer etching resulted in shorter nanowires (3.4 μm after 48 minutes). The improvements were ascribed to greater surface area, improved charge transfer, and lower optical losses.

However, the investigation was confined to certain etching conditions and material compositions. Future research should focus on the long-term stability, large-scale manufacturing, and multi-layered nanostructuring to boost efficiency even more.

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Дослідження морфології підкладки та електричних характеристик наноструктурованих кремнієвих сонячних елементів

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Морфологія підкладки відіграє життєво важливу роль у визначенні електричних характеристик наноструктурованих кремнієвих сонячних елементів (NSiSC), впливаючи на динаміку переносу заряду, оптичне поглинання та поверхневу рекомбінацію. Метою дослідження є вивчення впливу різних морфологій підкладки на електричні характеристики NSiSC, включаючи ефективність перетворення енергії (ЕПЕ), струм короткого замикання (СКЗ), коефіцієнт заповнення (FF) та напругу холостого ходу (V_{oc}). NSiSC було виготовлено з використанням підкладок з різною шорсткістю поверхні та текстурами. Для характеристики морфології поверхні використовувалися скануюча електронна мікроскопія (СЕМ) та атомно-силова мікроскопія (АСМ). Для дослідження кристалічної якості та фазового складу було проведено рентгенівську дифракцію (XRD). Для оцінки ефективності поглинання світла було записано спектри оптичного відбиття. Електричні характеристики вимірювалися за стандартних умов освітлення за допомогою сонячного симулятора. Результати дослідження показують сильну кореляцію між морфологією підкладки та електричними властивостями сонячних елементів. Шорсткіші поверхні демонстрували покращене захоплення світла, що призводило до збільшення щільності СКЗ. Порівняно з планарними підкладками, поверхні з нановізерунками демонстрували вищу щільність СКЗ, збільшення V_{oc} та покращений ЕПЕ. NSiSC-30/150 мав найвищий показник ЕПЕ (13,5%), з напругою холостого ходу 529 мВ, коефіцієнтом демпфування (FF) 67,5 % та коефіцієнтом підриву під напругою 37,8 мА/см^2.

Ключові слова: Морфологія підкладки, Електричні характеристики, Наноструктура, Кремнієві сонячні елементи, Ефективність поглинання світла.