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# ENHANCING THIRD-GENERATION SOLAR CELL EFFICIENCY AND STABILITY THROUGH P-TYPE SILICON INTEGRATION: PROCESS ANALYSIS AND PERFORMANCE EVALUATION

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Third-generation solar cells have emerged as a potential solution to the effectiveness and stability issues encountered in conventional solar technology. This study focuses on the characteristics of copper-zinc-tin-sulfide (CZTS) thin films inside this innovative architectural framework, which is an important step toward improving third-generation solar cells by incorporating a p-type silicon layer. This integrated method provides a versatile and manageable setting for film deposition, underscoring the effort put into creating high-quality CZTS thin films. Using X-ray diffraction (XRD), the study assessed the structural change of CZTS films after annealing, finding that kesterite phases were dominant. Images captured by a scanning electron microscope (SEM) reveal the microstructure and surface morphology of CZTS-coated Silicon nanowires (Si-NWs). A detailed analysis of the current-voltage characteristics provides evidence of the operational potential of the Si-NWs-CZTS coated solar cell. Significant performance parameters observed include a Voc value of 0.45 ± 0.02V, Isc value of 8.25 ± 0.30 mA/cm², FF value of 24 ± 2%, and η value of 1.0 ± 0.1%. The encouraging results indicate the capacity of using P-type silicon to enhance the performance of third-generation solar cells.
***Keywords:*** *Solar cells; CZTS; Thin film; Photovoltaics*
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## 1. INTRODUCTION

Rising societal interest in photovoltaic (PV) energy has contributed to a significant development in the demand for solar cells in the past few decades. The enhancement of energy conversion efficiency in solar cells via the advancement of innovations and technologies is crucial for the future global energy supply. However, a significant challenge associated with photovoltaic modules lies in their relatively expensive manufacturing and energy costs [1]. So, to provide low-cost third-generation solar cells, researchers are working to merge silicon substrates with thin coatings or nanostructures [2][3]. The third-generation solar cell is a viable alternative to traditional solar cell technologies. Its primary objective is to develop high-efficiency devices at a lower cost compared to the expensive 1-generation solar cells and the less effective 2-generation solar cells. Figure 1 given below illustrates the working concept of PV solar cells.

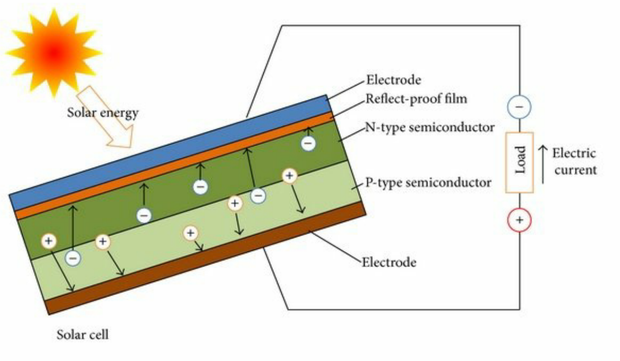


**Figure 1.** PV solar cell operational concept [4]

In light of the ongoing shift towards sustainability in the global energy sector, the pursuit of solar cells that are both efficient and stable has become of paramount importance. Solar cells combining n-type zinc oxide nanorods with p-type silicon have made great strides in recent years. This approach offers a cost-effective solution by employing inexpensive silicon wafers as substrates, hence reducing manufacturing costs [5][6]. Hence the present study contributes to this necessity by digging into the complex world of third-generation solar cells and concentrating especially on the influence of P-type silicon integration. The purpose of the study is to discover new horizons in solar technology by doing thorough process analysis and conducting rigorous performance assessments. This would pave the way for renewable energy sources that are more dependable and efficient.

The next parts of the study are arranged as follows: Section 2 provides the recent findings from studies aimed at improving the efficiency and reliability of solar cells. Section 3 addressed the research gaps based on conducted literature review. Section 4 explains the material and procedures utilized in the proposed study. The findings of the experiments

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are presented and discussed in the next section. Finally, Section 6 provides the conclusion of the study, including future considerations.

### 1.1 Advancements in Third-Generation Solar Cells

These types of solar cells aim for great efficiency and cheap cost by using a novel semiconductor nanoparticle method. The innovative notion of impact ionization may create a high current from semiconductor nanoparticles, making such devices very attractive. Shockley-Queisser efficiency limits the amount of energy that can be converted by solar cells thermodynamically, and it is believed that the use of semiconductor nanoparticles would overcome this barrier [7][8]. In the active layer of organic solar power cells, molecules may serve as both donors and acceptors. Till now a level of efficiency ranging from 10% to 15% has been attained [9]. Above 20% efficiency has been attained in perovskite solar cells using an integrated organic-inorganic perovskite halide and halogen active layer [10-12]. Additionally, emerging technologies such as multiband cells, and tandem and hot carrier solar cells, have shown promise in enhancing photocurrent and efficiency.

### 1.2 Various Third generation solar cell

Third-generation photovoltaics are broken down into five distinct categories, as described below [13]:

(i). Dye Sensitized Solar cell (DSSC)

The DSSC has gathered commercial interest due to its cheap production cost, semi-transparency, easy construction, and efficiency in low light [14]. DSSCs convert sunlight into energy using an electrolyte. DSSCs are simpler to make than standard cells because dye absorbs and passes sunlight to a semiconductor layer like $TiO_2$ [15][16]. Plant-based natural colors are safer for the environment and human health, but they don't last as long or seem as vivid as their synthetic counterparts [17]. Building integration, interior energy collection, smart farming, and more are possible with these solar cells [18][19].

(ii). Organic solar cells (OSCs)

OSC films of 100 nm are made from polymer compounds or molecules of organic semiconductors. They have a power conversion efficiency (PCE) of >18% [20] [21], are lightweight, cheap, easy to make, and ecologically favorable compared to silicon-based cells [22-24]. The use of star non-fullerene compound [25-28] and narrow-band-gap non-fullerene substance as a receiver [29] have improved the efficiency and stability of OSCs [30-33]. Organic semiconductors absorb more than inorganic ones. Adjusting the top electrode and using the proper material may maximize its conduction ability and average transmission of visible light [34].

(iii). Perovskite solar cells (PSCs)

In the last ten years, the PCE of PSCs has increased from 2% [35] to 28% in a tandem design. Short-lived stability and lead toxicity plague them. Encapsulating PSCs in epoxy resins instead of glass [36] improves mechanical stability, carbon-based monolithic PSCs improve thermal and humidity stability, controls crystallization over fabrication increases flexibility and scale, and tin dioxide ($SnO_2$) instead of $TiO_2$ solves scalability and stability issues [37].

(iv). Quantum dot solar cells (QDSCs)

Changing the size and structure of QDSCs, semiconductor tiny crystals, may rapidly modify their properties. Bulk materials in this region are difficult to produce but they may have seven changeable band gaps. QDSCs have several applications, including LEDs, FETs, and photodiodes [38]. These cells extract a broad sunlight spectrum effectively. Changing surface treatment may modify QDSC energy [39]. With a PCE of 16%, these cells are expected to be commercialized as flexible and portable PVs [40].

(v). CZTS

CZTS-based thin-film solar cells are safe for people and the environment [41]. CZTS solar cells use Copper-Indium-Gallium Selenide/Sulphide (CIGS), amorphous silicon (a-Si), and Cadmium Telluride (CdTe). CIGS has >20% efficiency despite raw material shortages. The most efficient kesterite solar cell has a 1.15 eV bandgap and 10.1% efficiency. Optimizing the deposition process, the kesterite absorbing-buffer layer contact and other approaches may boost CZTS cell efficiency.

## 2. LITERATURE REVIEW

In this section, some related studies by various authors on the enhancement of the productivity and efficacy of solar cells are discussed below:

**Sharma et al., (2021) [42]** detected that Solar cells have become smaller and converted more electricity over time. This study provides a comparative review of photovoltaic technology by conducting a comprehensive examination of the design, use, and performance of third-generation solar cells. It also explores the prospects and considerations associated with these solar cells. The findings revealed that concentrated solar cells have shown the highest efficiency of 38.9% among all kinds of solar cells.

**Peksu et al., (2020) [43]** revealed that the breakthrough in cheaper device production using materials for semiconductors that are very crystalline is a significant step toward advanced core-shell-based Si NWs solar cell technology for improved efficiency. Third-generation solar cells are made by covering transplanted NWs with a thin layer of CZTS for use in demonstrating products based on the NWs. In-depth characterization revealed the devices to have the best PCE of 1.31% for such material combinations and transmitted NWs.

**Tavakoli Dastjerdi et al., (2019) [44]** observed that a significant limitation on the widespread use of solar cells based on PbS quantum dots (QDs) is their sensitivity to humidity in the surrounding air. While oxygen doping the hole-carrying layer might fix this issue, doing so would be a lengthy and costly process. The study suggested a low-cost oxygen plasma treatment to improve performance and stability. The results revealed that the ideal treatment time for plasma is 10 minutes, which boosts PCE from 6.9% for the untreated device to 9% after treatment.

**Peksu et al., (2019) [45]** aimed to create a solar cell with the effectiveness of the 1-generation and the advantages of the third. A 1.0% efficient experimental Si-NW-CZTS structural solar cell was developed by applying a CZTS absorption layer coated with electroless etching on Si-NWs. The current density associated with a short circuit of the produced solar cell was much greater than that of the formerly described planer equivalency. This is crucial for the eventual growth of inexpensive, highly effective third-generation solar cells.

**Guller et al., (2018) [46]** performed the hydrothermal synthesis of TiO2 nanorods (NRs) on substrates of glass that have been coated with fluorine-doped tin oxide. The influence of growing conditions on synthesized NR morphology is examined. The findings showed that well-aligned TiO2 NRs need crucial physical conditions. After fine-tuning the growth parameters, a 3-generation inorganic-sensitized photovoltaic cell is built using organized TiO2 NR with a thin sputtered layer of CdTe. A PCE of 0.42% was achieved by the created solar cell, which is 3.5 times more than that of a non-$CdCl_2$-treated device structure.

**Wang et al., (2017) [47]** enabled the generation of hot charge carriers only from visible light by eliminating the need for UV light exposure by using plasmonically excited metal nanostructures that were included in a ZnO metal oxide layer. Additionally, the present study suggests solar cells with enhanced transport of charges and dispersion properties, along with greater light-trapping capabilities. The results show that there is potential to enhance the PCE of a low-bandgap solar cell, increasing from 7.91% to 9.36%.

**Wan et al., (2017) [48]** analyzed that Magnesium oxide/aluminum (MgOx/Al) connections are shown to be extremely conductive and thermally stable, allowing for Ohmic contacts with fairly low resistance on lightly doped n-type c-Si. Nanoscale $MgO_x$ films functionalized on the electrode significantly enhance the efficacy of n-type c-Si solar cells, bringing the PCE of these cells up to 20% and making them competitive with the standard p-type architecture.

**Zhu et al., (2017) [49]** employed a silicon-based nano heterostructure solar device to increase the light absorption provided by the NW array, and also by effectively separating charge carriers via the piezo-phototronic effect (PPE). It was observed that simply adding a static compress strain resulted in an efficiency increase of the solar cell from 8.97% to 9.51%. According to the findings of this study, PPE has the potential to enhance the effectiveness of large-scale Si solar cells, which has significant consequences for the industrial sector.

**Fix et al., (2016) [50]** suggested 3-generation solar cells to boost the effectiveness of conventional solar cells, such as CIGS or Si, which perform poorly when exposed to UV photons. The silicon photovoltaic cells have had encapsulants functionalized by photon-downshifting coordination complexes spin-coated onto their surfaces. The results show that all the coordination complexes show an enhanced ultraviolet spectrum sensitivity in solar cells and the suggested solar cell's conversion efficiency improved by 8%.

**Xu et al., (2014) [51]** observed that the addition of an organic redox shuttle to the photocathode of a sensitized $CuCrO_2$ delafossite nanocrystal electrode and a P1 sensitized organic dye could lead to an increase in photocurrent. In particular, it is shown that the presence of Au NPs inside the $CuCrO_2$ layer increases the electrical charge infusion performance at the dye/semiconductor junction.

## 3. RESEARCH GAPS

Some of the major research gaps that are addressed in this experimental study are as follows:

- Long-term stability evaluations of solar cells with integrated P-type silicon are ignored, and existing studies often focuses on shorter time frames.
- Previous study often exhibits a lack of comprehensive investigation into the various mechanisms associated with the incorporation of P-type silicon into third-generation solar cells.
- Although the potential improvements in efficiency and stability via the incorporation of P-type silicon are recognized, there is a lack of standard and comprehensive methods for assessing performance.

## 4. MATERIALS AND METHODS

The following section explains the methods and materials utilized in this experimental study.

### 3.1 EXPERIMENTAL PROCEDURE

The primary aim of this experimental design is to evaluate the impact of including a p-type layer on the efficacy and sustainability of thin-film Si solar cells. The primary emphasis is specifically placed on recognizing the properties of CZTS films throughout this particular architecture. The selected approach for the production of CZTS thin films involves the combination of spin-coated and sol-gel techniques. The selection of this technique is deliberate, as it has shown to be effective in tackling the problems often encountered during the synthesis of CZTS thin films with high stoichiometry. The use of both of these techniques provides a flexible and regulated setting for the deposition of films. The strategic selection of the manufacturing technique highlights the experimental approach's dedication to attaining CZTS thin films of superior quality and analyzing the overall efficiency and durability of thin-film silicon solar cells.

### 3.2 Materials Required

The crucial elements for the experimental undertaking include an appropriate range of materials which are given in Table 1. Along with these elements, the selected substrates for the deposition technique include soda lime glass (SLG) and arrays of p-type silicon NWs.

**Table 1.** Materials required and their properties

| Elements | Composition | Concentration/volume | Purity level |
|---|---|---|---|
| Copper acetate | $Cu(CH_3COO)_2$ | 1.7 M | 98% |
| Tin chloride | $SnCl_2$ | 0.7 M | 98% |
| Thiourea | $CH_4N_2S$ | 6.5 M | 99% |
| Zinc acetate | $Zn(CH_3COO)_2(H_2O)_2$ | 1.1 M | 99.9% |
| Triethanolamine | $N(CH_2CH_2OH)_3$ | 1.2 mL | 98% |
| 2-methoxyethanol | $C_3H_8O_2$ | 10 mL | 99% |

The materials that have been utilized in this experimental study serve as the basis for the succeeding phases of the experiment, guaranteeing a thorough and accurate assessment of the impact of the p-type coating on the efficiency and durability of CZTS Si-solar cells of the third generation.

### 3.3 Experimental Process

The procedure of film deposition is specifically arranged to guarantee the accuracy and excellence of the CZTS thin films. The initiation process entails the careful and thorough production of a solution via the dissolution of the designated components. The primary objective of this critical stage is to get a uniform blend, hence enhancing the uniformity of the film's characteristics. The solution is subjected to extensive agitation for 2 hours at ambient temperature, therefore further augmenting its uniformity.

Aging the solution for two days is a crucial step in the procedure. This time frame was specifically selected to optimize the final product quality of the thin films. After that, a 0.42 m syringe filter is used to further refine the solution and remove any remaining contaminants. Spin-coating at 3500 rpm for half a minute is used to deposit materials onto substrates like soda lime glass (SLG) and p-type Si-NW arrays. The uniformity of the thin films across substrates may be attributed in part to the controlled deposition method. The organic solvent is removed, and the thin films are made more stable by being heated at 220 degrees Celsius for 1.5 hours on a hot plate. After this well-managed thermal process, stable CZTS thin films are left behind, free of any lingering solvent.

After all layers have been deposited, their thicknesses must be measured. A surface profilometer is used for this purpose because it provides precise measurements that are essential for further analyses of the structure's strength and efficiency. Overall, the film deposition process is systematic and regulated, which ensures the dependability and repeatability of the CZTS thin films for further study.

### 3.4 Performance Parameters

This section includes numerous factors related to the evaluation of Si- based CZTS thin films' performance in third-generation solar cell applications. The section is organized with subheadings that explore distinct performance factors which are given as follows [45]:

#### 3.4.1 *Structural Characterization*

This study utilizes X-ray diffraction (XRD) for structural examination by exposure of CZTS lightweight films to X-rays to obtain information regarding the crystallographic orientation, material formulation, and phase purity that may be obtained from its crystalline structure.

#### 3.4.2 *Optical Properties*

This study utilized a spectrophotometer to determine the degree of reflection and transmission of the CZTS films and measure the intensity. In order to evaluate the material's transparency, absorbance, and reflectance, this examination offers a thorough comprehension of those optical qualities.

#### 3.4.3 *Solar Cell Fabrication*

Si NWs are layered with a thin CZTS sheet as part of the solar cell construction process. To maximize the absorption of light and electron production, the CZTS material must be integrated into the solar cell structure. Thermal evaporation is used to apply silver dot contacts roughly 60 nm thick on top of the CZTS coating. These silver connections are critical to the solar cell's functioning and conductivity, allowing for the effective removal of electrons that have been created. Apply a coating of silver thin film that is 150 nm thick on the unpolished side of the n-type silicon wafer. This silver sheet in the solar cell facilitates the effective collection of electrons produced by the photovoltaic process.

#### 3.4.4 *Photovoltaic Characterization*

The evaluation of the performance of solar cells may be conducted inside a controlled environment that simulates natural sunlight conditions. To begin the experiment, it is necessary to get measurements of the current-voltage characteristics of a photo-current-driven device under two distinct lighting conditions: low and intense light. The analysis of the solar cell's electrical response to varying levels of light is necessary. Subsequently, calculate the power conversion efficiency (η), open circuit voltage (Voc), short-circuit current (Isc), and fill factor (FF) of a solar array. To evaluate the viability of CZTS-based solar cells for practical implementation, a comprehensive analysis of their efficiency and performance is necessary.

## 5. RESULT AND DISCUSSION

The following section demonstrates the results obtained from the experimental study:

### 4.1 XRD result

Figure 2 shows XRD patterns illustrating the diffraction characteristics of CZTS thin films that have undergone both initial growth and subsequent annealing processes. These films were deposited onto substrates composed of single-layer graphene (SLG). The as-grown film's pattern may exhibit polycrystalline phases of kesterite CZTS and Cu2-xS. The phases in question are denoted by the peaks seen in the indexed reflection data. Based on the observed trend, it can be inferred that only the reflection peaks corresponding to Si (316) and CZTS (116, 212, and 230) can be seen.

During annealing, the kesterite CZTS phase becomes more dominant while the peaks associated with the secondary Cu2-xS phase fade. Increased intensity relative to angle is indicative of increased concentration or existence of the observed peaks related to CZTS.

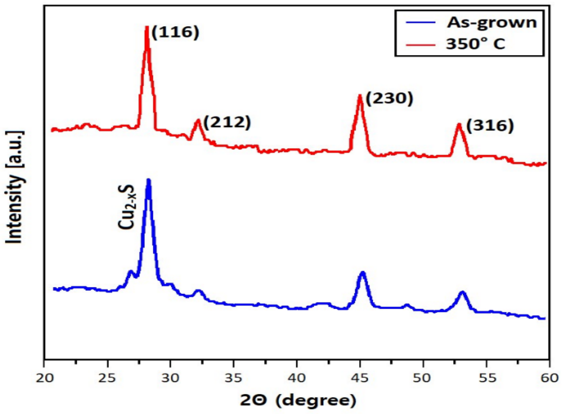


**Figure 2.** XRD patterns

### 4.2 SEM

Figure 3 (a-b) displays top-down and side-view SEM images of the incorporated Si-NWs. These images illustrate the microstructure and surface morphology of the Si-NWs in specifications, and they do so despite the requirement of any coatings or additional layers. Each CZTS-layered Si-NW illustrated in Figure 3 (c-d) is 600 nm thick. The SEM images illustrate the top-down view and side view. Immediately after deposition of the CZTS absorbent layer on the Si-NWs, these images were obtained.

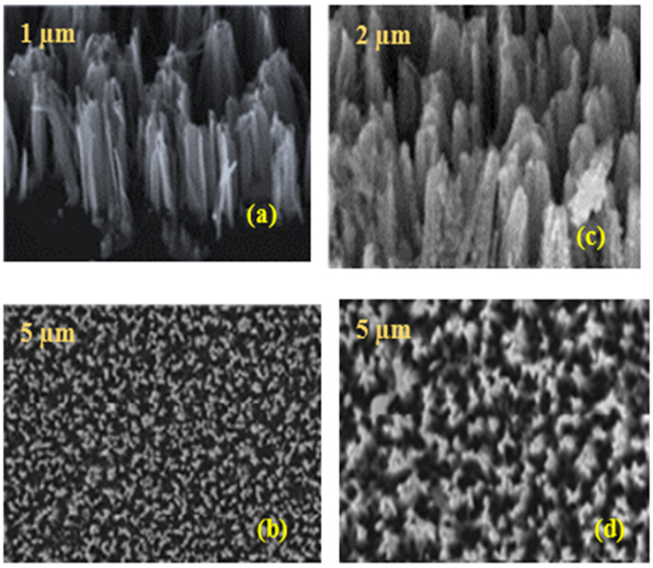


**Figure 3.** Top-down and side view of (a-b) Si-NWs (c-d) CZTS-layered Si-NW

The SEM images indicate that the CZTS layer is present as an extra overlay on the Si-NWs. The provided images facilitate the comprehension of the device configuration by elucidating crucial information on the shape and structure of CZTS-coated Si-NWs.

### 4.3 Current (I) -Voltage (V) Characterisation

The current (I) -voltage (V) relationship of the Si-NW-CZTS photovoltaic cells was evaluated in the presence of both dark conditions and AM 1.5G light. The characteristic curve illustrates the correlation between the current flowing (I) and voltages (V) across the solar cell. Figure 4 illustrates the same feature that has been transferred towards the I-1st quadrant, facilitating the analysis of the solar cell's effectiveness.

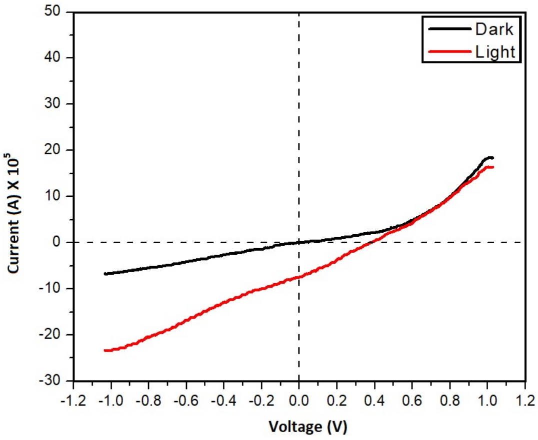


**Figure 4**. I-V relationship

This evaluation provides significant insights into the operational characteristics of the solar cell across varying levels of light, hence facilitating the determination of crucial parameters. The Voc of the designed Si-NW-CZTS solar cell was found to be 0.45 ± 0.02V. The Isc was estimated to be 8.25 ± 0.30 mA/cm$^2$. The FF was established to be 24 ± 2%. Lastly, the η of the solar cell was estimated to have a value of 1.0 ± 0.1%.

## 6. CONCLUSION AND FUTURE SCOPE

P-type silicon integrated into third-generation solar cells using CZTS layers atop Si-NWs has shown encouraging efficiency and stability results. After annealing, CZTS films transformed into dominant kesterite phases, improving their structural properties, according to XRD studies. SEM study clarified CZTS-coated Si-NWs' microstructure and surface morphology, revealing the photovoltaic device's configuration. The Si-NW-CZTS solar cell performance was shown by dark and light current-voltage measurements. Performance measurements of the solar cell include Voc of 0.45 ± 0.02V, Isc of 8.25 ± 0.30 mA/cm$^2$, FF of 24 ± 2%, and η of 1.0 ± 0.1%. These findings suggest that P-type silicon incorporation might boost third-generation solar cell efficiency.

Opportunities for further research into improving solar cell efficiency beyond the third generation have been established by the successful incorporation of P-type silicon. Future studies might concentrate on perfecting the integration procedure to boost efficiency and steadiness. Third-generation solar cells have several obstacles that can only be overcome by the combined efforts of researchers on a holistic approach to the problem.

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## ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ТА СТАБІЛЬНОСТІ СОНЯЧНИХ ЕЛЕМЕНТІВ ТРЕТЬОГО ПОКОЛІННЯ ШЛЯХОМ ІНТЕГРАЦІЇ КРЕМНІЮ P-ТИПУ: АНАЛІЗ ПРОЦЕСУ ТА ОЦІНКА ПРОДУКТИВНОСТІ

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Сонячні батареї третього покоління з'явилися як потенційне рішення проблем ефективності та стабільності, які виникають у традиційних сонячних технологіях. Це дослідження зосереджено на характеристиках тонких плівок міді-цинку-олова-сульфіду (CZTS) у цій інноваційній архітектурній структурі, яка є важливим кроком до вдосконалення сонячних елементів третього покоління шляхом включення шару кремнію p-типу. Цей інтегрований метод забезпечує універсальне та кероване налаштування для осадження плівок, підкреслюючи зусилля, докладені для створення високоякісних тонких плівок CZTS. Використовуючи рентгенівську дифракцію (XRD), дослідження оцінило структурні зміни плівок CZTS після відпалу, виявивлено, що кестеритові фази були домінуючими. Зображення, отримані скануючим електронним мікроскопом (SEM), демонструють мікроструктуру та морфологію поверхні покритих CZTS кремнієвих нанодротів (Si-NW). Детальний аналіз вольт-амперних характеристик свідчить про робочий потенціал сонячної батареї з покриттям Si-NWs-CZTS. Значні параметри продуктивності, що спостерігалися, включають значення Voc 0,45±0,02 В, значення Isc 8,25±0,30 мА/см², значення FF 24 ± 2 % і значення η 1,0±0,1 %. Результати вказують на можливість використання кремнію p-типу для підвищення продуктивності сонячних елементів третього покоління.

**Ключові слова:** *сонячні батареї; CZTS; тонка плівка; фотовольтаїка*