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Electrical Characteristics Analysis of High-Efficiency SnS Solar Cells

Ali Sadoun[1*], Nassiba Allag[2]

[1]Applied Materials Laboratory, Research Center (CFTE), Sidi Bel Abbès Djillali Liabes University, 22000, ALGERIA
[2]Technology Faculty, University of El Oued, ALGERIA

*Corresponding author E-mail: 3ali39@gmail.com

Abstract – *The simulation of SnS homojunction solar cells involved systematically adjusting key parameters, such as doping concentration and layer thickness, to optimize their photovoltaic performance. The study identified that optimal efficiency is achieved with a carrier concentration of 5.5 × 10^{15} cm^{-3} in the front n-type region, a 500 nm thick n-layer, and a 500 nm thick p+ layer with a carrier concentration of 3 × 10^{16} cm^{-3}. Under these conditions, the solar cell demonstrated excellent electrical characteristics, including an open-circuit voltage (Voc) of 0.90 V, a short-circuit current density (Jsc) of 34.20 mA/cm², a fill factor (FF) of 0.829, and an efficiency (η) of 25.71%. These results underscore the importance of precise control over material properties and structural dimensions in achieving high-efficiency SnS-based solar cells, positioning SnS as a promising material for future photovoltaic applications.*

Keywords: Simulation, homojunction, Solar cells, SnS.

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I. Introduction

Laboratory research in green energy is increasingly concentrating on developing cost-effective and efficient alternatives to conventional fuel sources, with a strong emphasis on advancements in photovoltaic technologies. Among the materials being explored, Tin(II) sulfide (SnS) stands out for its conductive and semiconductive properties. Optimizing SnS involves investigating various deposition techniques and carefully controlling processing conditions, such as temperature, to enhance its material properties. These factors are crucial in determining the energy conversion efficiency of the resulting solar cells. In addition to these experimental efforts, simulation tools and the investigation of alternative materials are employed to further boost the efficiency, stability, and overall performance of solar cells, driving the development of more sustainable and reliable renewable energy solutions [1-5]

Tin (II) sulfide (SnS) is a compound made up of tin and sulfur, represented by the chemical formula SnS. This material has a wide range of applications, including use in solar cells, sensors, and optoelectronics, due to its unique electrical and optical properties. The tin sulfide (SnS) thin films were grown using the sol–gel spin-coating technique on glass substrates, and their properties were extensively characterized. Techniques such as X-ray diffraction (XRD), photoluminescence (PL), UV–Vis spectroscopy, and the four-point technique were employed to analyze the films. It was found that annealing at 500 °C resulted in films with good crystalline quality and an orthorhombic phase. The optical and electrical properties of these SnS layers, particularly those annealed at 400 °C and 500 °C, were deemed highly suitable for photovoltaic applications. Additionally, theoretical analysis of an Au/InSb/InP Schottky diode using current-voltage (I-V) measurements over a temperature range of 300 K–425 K revealed crucial electrical parameters, including a Schottky barrier height (Φb) of 0.602-0.69 eV, ideality factors between 1.683-1.234, and series resistance values ranging from 84.54 to 18.95 Ω.[6, 7].

SnS is seen as a promising material for various electronic and photonic devices. Simulations of Au/n-GaN and

PEDOT/GaN structures were performed at room temperature to calculate electrical parameters such as barrier height, ideality factor, shunt resistance, and series resistance. Using various methods including conventional I-V, Norde, Chattopadhyay, and Mikhelashvili methods, the Au/GaN structure was found to have a higher barrier height (0.72 eV) compared to the PEDOT/GaN structure (0.6 eV), with ideality factors of 1.88 and 2.26, respectively. The shunt resistance increased from 77,150.056 Ω to 11,207,586 Ω, while the leakage current increased from 6.64E-5 A to 4.98926E-5 A at −0.85 V [8,9]. Researchers have extensively studied its characteristics with the aim of improving photovoltaic applications. They have found that SnS can significantly enhance the efficiency and cost-effectiveness of solar cells due to its high absorption coefficient in the visible and near-infrared regions of the spectrum, which is ideal for converting solar energy. Additionally, the optimal band gap energy for effective photovoltaic performance of SnS is reported to be around 1.1-1.2 eV [10].

In research efforts, one study focused on SnS thin films produced through a cost-effective solution-based method, while another employed density functional theory calculations to analyze the electronic and optical properties of SnS. Both studies suggest that SnS holds significant promise as a low-cost and efficient material for photovoltaic devices[11-14].

SCAPS (Solar Cell Capacitance Simulator) is a specialized simulation program used to predict the performance of photovoltaic devices, such as SnS solar cells. The efficiency of these solar cells depends on various factors, including device design, fabrication techniques, and material properties. In recent years, there has been growing interest in using SCAPS software to enhance the efficiency of tin sulfide (SnS) thin-film solar cells [15].

The objective of this work is to perform a comprehensive numerical analysis and optimization of the electrical characteristics of SnS homojunction solar cells. By adjusting critical parameters including doping concentration and layer thickness, the study aims to identify the optimal configuration that maximizes the energy conversion efficiency of the solar cells. This work aims to provide a highly efficient design that can serve as a basis for future experimental validation and practical application in photovoltaic technologies. Novel features of this study include a targeted simulation approach to fine-tune the balance between charge carrier collection and recombination rates, leading to a detailed understanding of the optimal conditions to achieve maximum efficiency in SnS-based solar cells.

II. Methodology

II.1. Simulation Parameters

The simulation of SnS homojunction solar cells was conducted using a numerical modeling approach, focusing on optimizing key parameters to enhance the device's performance. The parameters adjusted during the simulation included the doping concentration and the thickness of the n-type and p+-type layers. The n-layer was simulated with a thickness of 500 nm and a carrier concentration of 5.5×10^{15} cm^{-3}, while the p+ layer was also set to 500 nm thickness but with a higher carrier concentration of 3×10^{16} cm^{-3}. These values were chosen to optimize the balance between charge carrier collection and recombination rates, aiming to maximize the overall efficiency of the solar cell.

II.2. Performance Evaluation

The electrical performance of the solar cells under these optimized conditions was evaluated by calculating the open-circuit voltage (Voc), short-circuit current density (J), fill factor (FF), and overall power conversion efficiency (η%). The simulation results revealed that with the specified parameters, the SnS homojunction solar cell achieved a Voc of 0.90 V, a J of 34.20 mA/cm², an FF of 0.829, and an efficiency of 25.71%. These values indicate that the chosen parameter set offers a highly efficient configuration for SnS-based solar cells, providing a robust foundation for further experimental validation and potential real-world application.

III. Result and discussion

III.1. Current-voltage characteristics

Figure 1 illustrates the highest achievable performance of the n-SnS/p-SnS homojunction solar cell, demonstrating an efficiency of 25.70%, an open-circuit voltage (Voc) of 0.905V, a short-circuit current density (Jsc) of 34.202mA/cm², and a fill factor (FF) of 0.82999. These simulated results show a marked improvement in photovoltaic performance compared to the much lower values reported in previous studies[16]. For instance, in a study conducted by Shuo Lin et al. [17] , the efficiency, Voc, Jsc, and FF were found to be 25.2%, 0.98V, 29.31mA/cm², and 0.876, respectively. A comparative analysis of these findings with various experimental and simulated data reveals a significant congruence in values, highlighting the reliability and accuracy of the results.

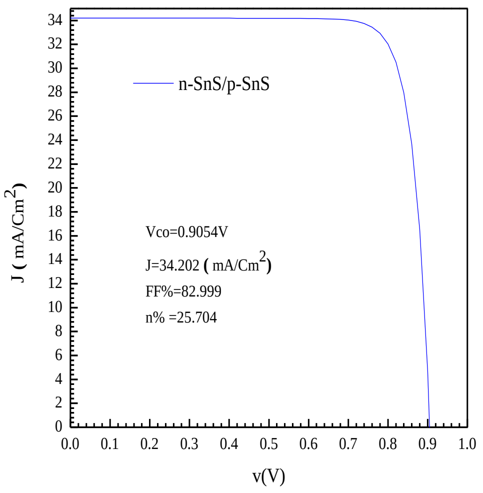

Figure. 1. Current-voltage characteristics of n_SnS / p_SnS solar cells

Using the findings from this phase of the study, we investigated how different factors impact the efficiency of a p+_SnS absorber layer in a solar cell. We specifically investigated how variations in operating temperature, series resistance (Rs), doping concentration (NA), and thickness of the p+_SnS absorber layer affect the efficiency and stability of the device. We conducted experiments with various values for each parameter, including an operating temperature ranging from 280 K to 400 K, a Rs ranging from 0 to 7 Ohm, a NA ranging from 1E13 to 1E17 Cm3, and a thickness of the p+_SnS absorber layer ranging from 0 to 4 µm. Through the manipulation of these factors, our objective was to determine the most favorable circumstances for enhancing the device's performance and attaining enhanced efficiency in the solar cell [18].

III.2. Operating temperature Effects for structure solar cells

The operational temperature of a solar cell significantly affects its performance, especially for solar panels installed outdoors, where temperatures often exceed 300 K. Increased temperatures can cause stress, pressure, interfacial defects, and poor interconnectivity between layers. In our study, we varied the working temperature from 280 K to 400 K while keeping all other parameters constant. We then assessed the impact of these temperature changes on the key characteristics of the device, as illustrated in Figure 2.
The simulation results revealed that the maximum efficiency of approximately 28.57% was attained at a relatively low temperature of 280 K. However, as the temperature increased, efficiency declined due to the reduced mobilities of holes and electrons and the lower carrier concentration. Although the short-circuit current density (Jsc) exhibited a slight increase with rising temperature due to the generation of additional electron-hole pairs, the open-circuit voltage (Voc) decreased because of increased interfacial defects, higher series resistance, and lower carrier diffusion [19].

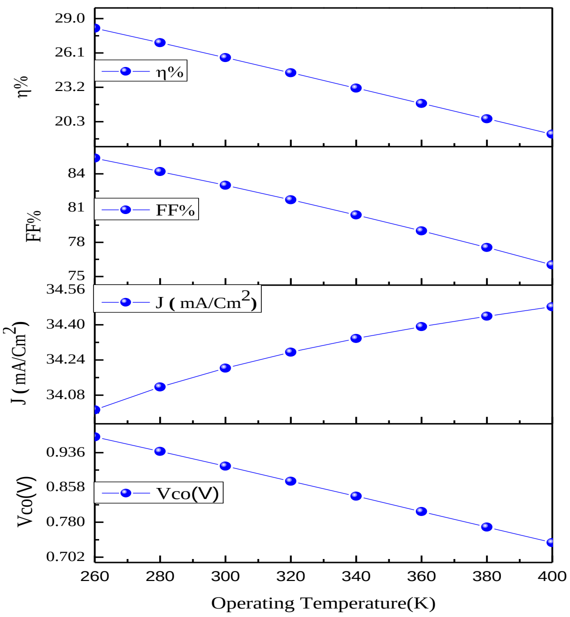

Figure. 2. Effects of operating temperature for n_SnS / p+_SnS/ p_SnS solar cells

III.3. Series resistance (Rs) effect on a solar cell

Figure 3 depicts the impact of varying series resistances (Rs) on the key performance parameters of the simulated solar cell, including open-circuit voltage (Voc), short-circuit current (Isc), fill factor (FF), and efficiency (η). The Rs value accounts for the internal resistance of the device, encompassing both the resistance within the active layer and the Ohmic contact resistance. The results indicate that increasing Rs did not significantly influence the open-circuit voltage (Voc), as shown in Figure 3(a). However, it led to a noticeable decrease in the short-circuit current (Isc), as illustrated in Figure 3(b). Additionally, Figure 3(c) demonstrates the effect of increasing Rs on the fill factor (FF), revealing a significant reduction as Rs increases. This highlights the detrimental impact of higher series resistance on the overall performance of the solar cell [20].

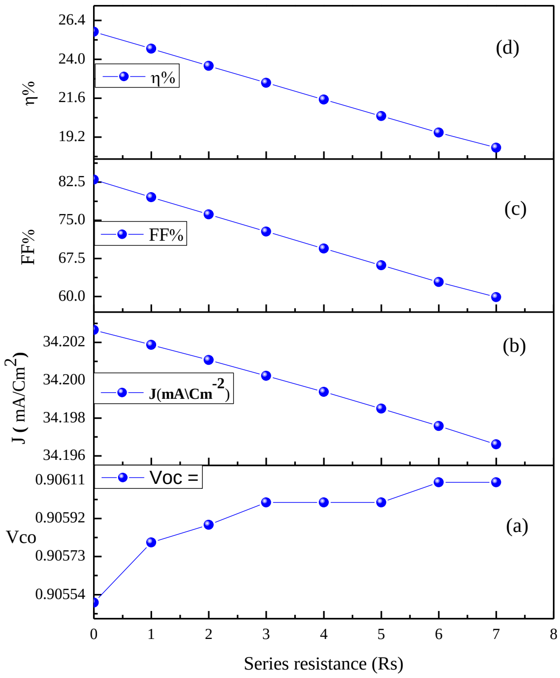

Figure. 3. Effects of series resistances for n_SnS / p+_SnS/ p_SnS solar cells

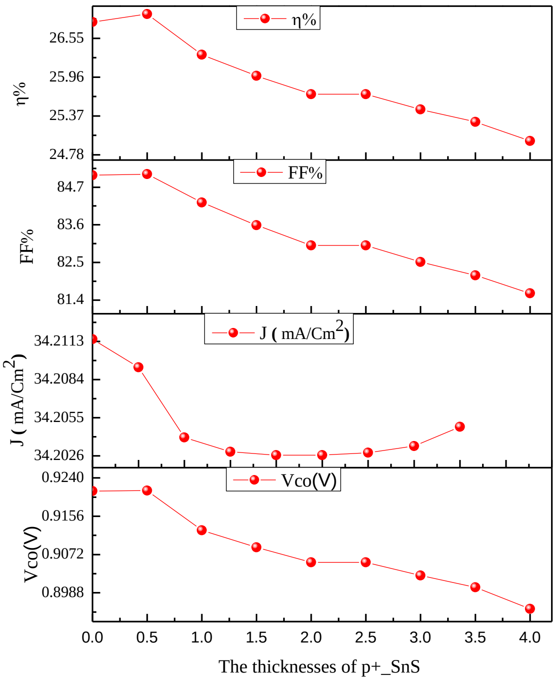

Figure. 4. Effects of thickness of p+_SnS solar cells

III.4. Thickness optimization of the p-SnS layer

The study conducted a numerical simulation of a photovoltaic (PV) device with an n_SnS / p+_SnS / p_SnS structure, where the thickness of the p+_SnS absorber layer was varied between 0 µm and 4 µm. The simulation results indicated that as the thickness of the absorber layer increased, the short-circuit current density (Jsc) varied, while the open-circuit voltage (Voc) remained nearly constant. According to Figure 5, the optimal thickness for the p+_SnS layer was determined to be 0.5 µm. The solar cell's efficiency was observed to increase with greater absorber layer thickness up to 0.5 µm, beyond which it began to decrease. This decline in efficiency was attributed to increased carrier recombination, which reduced the number of electrons contributing to the overall efficiency of the solar cell.

III.5. Effect of the doping concentration (NA)on a solar cell

The carrier concentrations, particularly the doping concentration in the p-type region, significantly influence the short-circuit current density (Jsc) and the open-circuit voltage (Voc) of the solar cell. As illustrated in Figure 5, an increase in the doping concentration (Ni) within the p-type region leads to a decrease in Jsc, while Voc increases with the rise in Ni. The value of Voc can be determined using equations (1) and (2), which indicate that an increase in Ni leads to a corresponding increase in Voc.

$$V_{oc} = \frac{kT}{q} \ln(\frac{J_{sc}}{J_0} + 1) \quad (1)$$

$$J_0 = q n_i^2 (\frac{D_n}{L_n N_A} + \frac{D_P}{L_P N_D}) \quad (2)$$

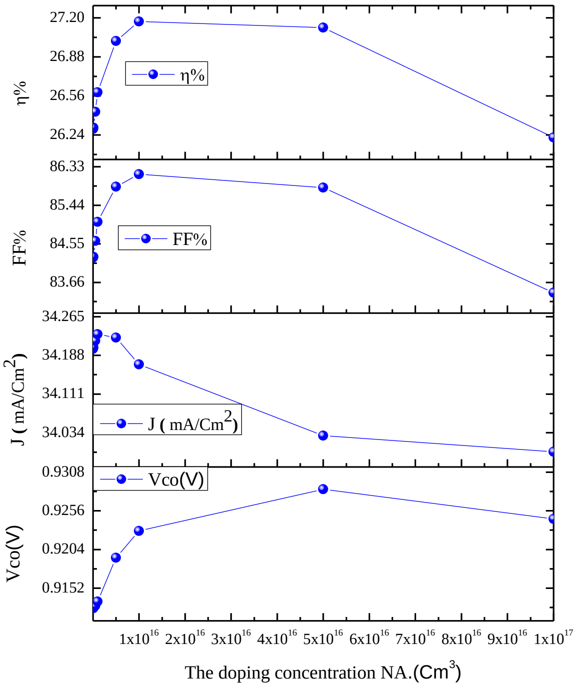

Figure. 5. Effect of the doping concentration (NA)on a solar cell

IV. CONCLUSION

This simulation study was conducted to evaluate the photovoltaic performance of n-SnS/p+-SnS/n-SnS solar cells in different architectures by systematically varying the doping concentrations and layer thicknesses. The analysis revealed that the electrical characteristics of SnS homojunction solar cells are highly sensitive to these parameters, which significantly influences the overall device efficiency. Through careful optimization, an optimal configuration was identified that yielded a power conversion efficiency of 25.71%, characterized by an open circuit voltage (Voc) of 0.90 V, a short circuit current density (Jsc) of 34.20 mA/cm², and a fill factor (FF) of 0.829. These results highlight the importance of precise control of doping concentrations and layer thicknesses to achieve high-efficiency SnS-based solar cells. The results provide valuable insights for the design of future photovoltaic devices, highlighting the potential of SnS as a viable material for high-performance solar cells. The optimized configuration serves as a solid basis for further experimental validation, with the potential to significantly contribute to the development of cost-effective and environmentally friendly photovoltaic technologies.

Declaration

- The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.
- The authors declare that this article has not been published before and is not in the process of being published in any other journal.
- The authors confirmed that the paper was free of plagiarism.

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